# INTERNAL RESEARCH REPORT

## 2021-2022


**Programme Leader**

Dr. Md. Anower Hossain

Chief Scientific Officer (In-charge & Head)



Irrigation and Water Management Division

Bangladesh Agricultural Research Institute

Joydebpur, Gazipur-1701

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# PREFACE

*The principal objective of irrigation and water management research is to determine how best the water resources, be it from underground, surface or rainfall can be utilized for crop production and how to minimize the harmful effect of this water. This inevitably demands research on how to exploit available sources of water, convey and distribute them to farms and apply the same to the individual crop field. The next important aim is to increase the crop water use efficiency in order to obtain maximum production per unit drop of water thereby increasing economic return and improving livelihood of the farmers. To achieve this goal, research need to be conducted on when and how much water should be applied, and when irrigation is not necessary at all.*

*The general objectives of the division are to conduct research on: a) proper irrigation scheduling and rain water management of the upland crops and drainage thereof, b) finding appropriate technologies for conveyance, distribution, application and utilization of water resources for crop production, c) assessment of ground water reserves and its development for agricultural use, d) water management in saline and drought prone areas e) wastewater management f) micro irrigation, and g) impact of climate change on irrigated agriculture.*

*There are great potentialities that need to be developed in the management of ground and surface water resources. In many crops improved irrigation system has the potential to double the production. Rice crop, on average, require 1000 mm of water for the growing season whereas most upland crops require 200 to 500 mm water when applied efficiently. All these indicate that there remains tremendous possibility of increasing crop production by bringing more upland crops under irrigation and by properly controlling and managing the available water resources.*

*The task requires, amidst others, research in larger scale and in diversified crops. However, the division has got a very limited number of scientists and facilities to address the aforementioned research problems. With this manpower and facilities, we are trying our best to the benefit of our agricultural concerns.*

*Research and development activities of Irrigation and Water Management Division are directed towards the economic development of the country. The division is working to help the nation becoming self-sufficient in food, to generate employment in agriculture and to increase income of farmers through the development of appropriate water management practices and techniques widely acceptable to all categories of farmers. This report presents the findings of both on-station and on-farm studies conducted during 2021-22. This year, the division carried out researches in the areas of crop water requirement and irrigation scheduling, water application and distribution methods, on-farm water management, saline and wastewater management, groundwater management and dissemination of developed water saving technologies at the farmer's level and improvement of farmers' traditional irrigation practices.*

*Finally, I like to express my sincere thanks to the scientists/staffs concerned with these studies and to all who helped in bringing out this report.*

**Dr. Md. Anower Hossain**
Chief Scientific Officer (in-charge) and Head

# CONTENTS

# RESPONSE OF MUNGBEAN TO DIFFERENT LEVELS OF IRRIGATION

S. S. A. KAMAR[1], S. K. BISWAS[2], M. A. HOSSAIN[3], M. R. UDDIN[4], RAJIUDDIN[5] AND M. A. RAHMAN[6]

## Abstract

*To increase crop and soil productivity in single rice cropped areas of Bangladesh, mungbean is being considered for the dry period. Due to uncertainties in onset, frequency, and amount of pre-monsoon rainfall, the yield of mungbean often hampered by shortage of water, with its incidence and severity exacerbated by the present long term dry period effect in agriculture. This study examined the potential benefits of different levels of irrigations on mungbean cultivation at two different agro environmental region (Gazipur and Barishal). The experimental design was randomized complete block and the plots were distributed into three replications. Four different levels of irrigation (control, irrigation at early vegetative stage, irrigation at early vegetative stage and flowering stage and lastly irrigation at early vegetative stage and pod formation stage) were used to determine the most efficient water productive irrigation system for mungbean cultivation. With irrigation (at early vegetative stage and flowering stage), yields were greater (1215.94 kg/ha at Gazipur and 1434.67 kg/ha at Barishal) than without irrigation treatment (1029.00 kg/ha at Gazipur and 1077.67 kg/ha at Barishal) at both locations. When mungbean were irrigated, yields were also increasing according to the irrigation levels. Smaller yields in all scenarios were associated with either water deficit stress or waterlogging stress. Results indicate that mungbean productivity in single rice production systems in Bangladesh could be increased by managing irrigation levels and selecting optimum planting time. Farmers could acquire higher yield, water productivity and as well as profit.*

*Keywords: Mungbean, irrigation, yield, water productivity, benefit cost ratio.*

## Introduction

Mungbean (*Vigna radiata* (L.) Wilczek), a popular pulse crop with good test and important source of plant protein (19.5 to 28.5% proteins), has been widely cultivated throughout the world especially in Asian sub-continent including Bangladesh (Lambrides and Godwin, 2006). In Bangladesh the present area under mungbean cultivation is 101 thousand acres with a total production of 37 thousand ton and an average yield of 351 kg acre-1 (BBS, 2016). The crop is cultivated either during early *kharif* or late *rabi* season (March to June). Several biotic and abiotic stresses either singly or collectively caused adverse effect on mungbean plant resulting poor growth and development. Abiotic stresses including drought, have been reported as major constraints to the mungbean production projecting more than 50% of yield loss (Gaur *et al.*, 2012). Mungbean is sensitive to both low and high soil moisture (Trung et al. 1985a,b) and is especially vulnerable to excessive rainfall as it approximates maturity (Imrie et al. 1988). In wet periods, SWTs increase the likelihood of waterlogging problems, but in dry periods they are beneficial for meeting part or all of the crop water requirement through upward capillary flux (Ragab and Amer, 1986; Williamson and Kriz, 1970; Hundal and de Datta, 1984; Wallender et al.,1979). Soil water deficit or drought stress is considered as a severe threat to sustainable agriculture and food security (Foley *et al.*, 2011). The concern is very much alarming to the country like Bangladesh where it is more likely to face the consequences of different anthropogenic activities that might increase the severity of drought stress at near future. It has become a great need for the understanding of drought tolerance mechanisms prior to development of major drought tolerant varieties to achieve sustainable production goal of crop. Plants follow several strategies including morpho-physiological and molecular changes for the acclimation in drought stress. Drought induced several developments of plants seemingly adjust the water crisis either by the alteration of morphological, physiological or both to overcome the soil moisture stress. Physiological adaptation increases the accumulation of osmolytes and adjusted osmotic potential by reducing cellular dehydration (Omprakash *et al.,* 2017). Increased accumulation of proline has been reported in mungbean during drought (Bharadwaj *et al.,* 2018), nevertheless detail understanding of

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morphological and physiological alteration for screening of mungbean varieties based on the tolerance characteristics mentioned above should be very essential to adjust and mitigate the upcoming challenges. The problem is widespread in the southern part of the country where mungbean production is hampered to a great extent by the existing water limiting condition.

## Materials and methods:

The experiment was conducted at the experimental field of IWMD and RARS, Rahmatpur, Barishal during January, 2022 to April, 2022 to determine the effect of irrigation at different growth stages of mungbean and to understand the effects of irrigation on yield and yield components of mungbean. The test crop was BARI mug-8. This variety become popular due to the stress tolerant characteristics. The recommended doses of urea, triple super phosphate, muriate of potash, gypsum and boron at the rate of 45, 90, 45, 55 and 10 kg/ha were applied at the time of land preparation. The first weeding was done manually at 20 DAS and also the thinning was done; the rest of the plants were uprooted carefully to avoid disturbance to the nearby plants.

Experimental design

The experiment consisted of one factors: irrigation. Irrigation had four levels or treatments. Irrigation was scheduled based on the depth of water required. The irrigation treatments were allocated to the plot through flood irrigation. The irrigation treatments were:

1. Control (No Irrigation)
2. Early vegetative stage (10-15 days after emergence)
3. Early vegetative stage (10-15 days after emergence) + Flowering stage (35-40 days after emergence)
4. Early vegetative stage (10-15 days after emergence) + Pod formation Stage (45-50 days after emergence)

Quantification and application of irrigation water

Irrigation was applied based on the depth of water required. The procedure of calculating irrigation water is summarized below

$$d_{ir} = \sum_{i}^{n} \frac{(FC - RL_i) \times As_i \times D_i}{100}$$

Here,

$d_{ir}$ = Depth of irrigation water to be applied within the one irrigation cycle (mm),

FC = Mean soil moisture content at field capacity (%),

$RL_i$ = Residual soil moisture level before each irrigation in the $i^{th}$ layer of soil profile (%)

$As_i$ = Apparent Specific Gravity of the $i^{th}$ layer of soil,

$D_i$ = Depth of the $i^{th}$ layer of the soil profile within the root zone to be irrigated (mm),

Irrigation was applied by using power sprayer and no excess water was applied in the plots. In this case volume of water was measured by the following equations.

$V = a \times d$ ($m^3$)

Here, V= Volume of water in $m^3$

a= area of the plot in $m^2$

d= depth of water applied (m)

The following data was collected from the sample plants

- Plant Population
- Plant height (cm)
- Number of pod/plant
- Number of seed/pod
- 1000 seed weight (gm)
- Yield (kg/ha)

Water productivity

The water use of a crop field is generally described in terms of water productivity (WP), which is the ratio of the crop yield to the total amount of water used in the field during the entire growing period of the crop. The WP demonstrates the productivity of water in producing crop yield. WP for maize was calculated by:

$$WP = \frac{Y}{SWU} \quad (2)$$

Where, WP = Water Productivity, $kg/m^3$
Y = Grain yield, $kg/m^2$
SWU = Seasonal water use in the crop field, m

The WU was calculated by summing up the water applied in irrigation (taking into account the rainfall) and soil moisture contribution.
Data analysis
The collected data were analyzed using R and the mean differences were adjusted by LSD.

**Results and discussion**

The results represent the yield and yield contributing characters of BAR mug-8 at different irrigation levels. Table 1 describes the results obtained from IWMD research field during 2021-22. The results showed that the plant height was varied significantly at different irrigation levels and the highest (38.33 cm) plant height was found at treatment $T_3$ whereas the lowest (32.33 cm) was observed at treatment $T_2$. The plant population was observed statistically significant among the treatments. The highest (31) plant population was observed at treatment $T_3$ whereas the lowest (28) plant population was observed both at $T_1$ and $T_4$, respectively. The number of pod/plant was also perceived statistically significant from Table 1. The number of pod/plant was observed highest (40) at treatment $T_3$ on the other hand the lowest (25) number of pod/plant was perceived at $T_1$ treatment. Number of seed/pod, 1000 seed weight and yield were seemed statistically insignificant among different irrigation levels (Table 1). The yield of mungbean was observed highest (1215.94 kg/ha) at treatment $T_3$ and the lowest (1029.00 kg/ha) yield was observed at treatment $T_1$.

Table 1. Yield and yield contributing characters of mungbean cultivation at IWMD research field

| Treatments | Plant height (cm) | Plant population | Number of pod/plant | Number of seed/pod | 1000 seed weight (gm) | Yield (kg/ha) |
|---|---|---|---|---|---|---|
| $T_1$ | 33.78 | 28.00 | 25.00 | 10.00 | 33.67 | 1029.00 |
| $T_2$ | 32.33 | 30.00 | 28.00 | 11.00 | 32.33 | 1029.35 |
| $T_3$ | 38.33 | 31.00 | 40.00 | 11.00 | 32.33 | 1215.94 |
| $T_4$ | 34.22 | 28.00 | 28.00 | 11.00 | 32.33 | 1035.77 |
| CV(%) | 7.27 | 4.48 | 7.28 | 6.28 | 3.02 | 9.76 |
| LSD | 5.04 | 2.66 | 4.41 | - | - | - |

The results represent the yield and yield contributing characters of BAR mug-8 at different irrigation levels. Table 1 describes the results obtained from RARS, Rahmatpur, Barishal research field during 2021-22. The results showed that the plant height was varied significantly at different irrigation levels and the highest (58.33 cm) plant height was found at treatment $T_4$ whereas the lowest (43.13 cm) was observed at treatment $T_1$. The plant population was observed statistically insignificant among the treatments. The highest (32) plant population was observed at treatment $T_2$ whereas the lowest (29) plant population was observed both at $T_4$. The number of pod/plant was also perceived statistically significant from Table 1. The number of pod/plant was observed highest (148.00) at treatment $T_3$ on the other hand the lowest (43) number of pod/plant was perceived at $T_1$ treatment. Number of seed/pod was observed highest (13.00) at treatments $T_3$ and $T_4$, respectively and the lowest number of seed/pod was observed at $T_1$ treatment. The number of seed/pod was perceived statistically significant among the treatments. 1000 seed weight and yield were seemed statistically significant among different irrigation levels (Table 1). The 1000 seed weight was observed highest (31.20 gm) at treatment $T_4$ whereas the lowest 1000 seed weight was observed at $T_3$ treatment. The yield of mungbean was observed highest (1434.67 kg/ha) at treatment $T_3$ and the lowest (1077.67 kg/ha) yield was observed at treatment $T_1$.

Table 2. Yield and yield contributing characters of mungbean cultivation at RARS, Barishal research field

| Treatments | Plant height (cm) | Plant population | Number of pod/plant | Number of seed/pod | 1000 seed weight (gm) | Yield (kg/ha) |
|---|---|---|---|---|---|---|
| $T_1$ | 43.13 | 31.00 | 43.00 | 10.00 | 31.00 | 1077.67 |
| $T_2$ | 49.00 | 32.00 | 98.00 | 12.00 | 31.03 | 1211.33 |
| $T_3$ | 57.27 | 31.00 | 148.00 | 13.00 | 30.63 | 1434.67 |
| $T_4$ | 58.33 | 29.00 | 138.00 | 13.00 | 31.20 | 1256.67 |
| CV(%) | 7.67 | 5.37 | 7.67 | 4.56 | 1.26 | 3.47 |
| LSD | 7.96 | - | 16.37 | 1.09 | 0.78 | 86.37 |

Water productivity:

Table 3 and 4 represents the overall amount of water applied to each irrigation and the water productivity for cultivating mungbean at IWMD reseach field, Gazipur and RARS, Rahmatpur, Barishal. As the $T_1$ characterizes as the control treatment so that no irrigation was applied at $T_1$ for both locations. Only effective rainfall was used for calculating water productivity. From Table 3 and 4, it was perceived that the water productivity was higher at control treatment than other treatments. The water productivity was observed 0.92 kg/m$^3$ and 2.27 kg/m$^3$ at treatment $T_1$ for both the locations, respectively.

Table 3. Water productivity of mungbean cultivation at IWMD research field

| Treatment | Amount of total irrigation (cm) | Effective Rainfall (cm) | Total water use (cm) | Water productivity (kg/m$^3$) | Yield (kg/ha) |
|---|---|---|---|---|---|
| $T_1$ | 0.00 | 11.20 | 11.20 | 0.92 | 1029.00 |
| $T_2$ | 1.49 | 11.20 | 12.69 | 0.81 | 1029.35 |
| $T_3$ | 2.13 | 11.20 | 13.33 | 0.91 | 1215.94 |
| $T_4$ | 2.55 | 11.20 | 13.75 | 0.75 | 1035.77 |

Among the irrigated treatments ($T_2$, $T_3$, and $T_4$), the water productivity was perceived higher (0.91 kg/m$^3$ and 1.71 kg/m$^3$) at $T_3$ treatment for both the locations. $T_4$ treatment provided the lowest (0.75 kg/m$^3$ and 1.46 kg/m$^3$) water productivity at both IWMD and RARS research field, respectively. As the highest amount of water was applied at $T_4$ treatment the water productivity was found lowest.

Table 4. Water productivity of mungbean cultivation at RARS, Rahmatpur, Barishal research field

| Treatment | Amount of total irrigation (cm) | Effective Rainfall (cm) | Total water use (cm) | Water productivity (kg/m$^3$) | Yield (kg/ha) |
|---|---|---|---|---|---|
| $T_1$ | 0.00 | 4.75 | 4.75 | 2.27 | 1077.67 |
| $T_2$ | 2.37 | 4.75 | 7.12 | 1.70 | 1211.33 |
| $T_3$ | 3.65 | 4.75 | 8.40 | 1.71 | 1434.67 |
| $T_4$ | 3.85 | 4.75 | 8.60 | 1.46 | 1256.67 |

Economic analysis

Table 5 comprises, the cost calculation for mungbean cultivation at both Gazipur and Barishal. Except irrigation cost, rest of the costs were remained same for mungbean cultivation. Among all irrigation levels control treatment provided low cultivation cost than others due to no irrigation cost was required for mungbean cultivation at $T_1$ treatment. The highest cultivation cost was observed at treatment $T_3$ and $T_4$ due to higher irrigation cost at that two treatments.

Table 5. Cost calculation for mungbean cultivation

| Treatment | Land preparation (tk/ha) | Seed (tk/ha) | Fertilizer and pesticide (tk/ha) | Irrigation (tk/ha) | Labor (tk/ha) | Total Cost (tk/ha) |
|---|---|---|---|---|---|---|
| $T_1$ | 8645 | 3000 | 15350 | 0 | 30000 | 56995 |
| $T_2$ | 8645 | 3000 | 15350 | 6175 | 30000 | 63170 |
| $T_3$ | 8645 | 3000 | 15350 | 12350 | 30000 | 69345 |
| $T_4$ | 8645 | 3000 | 15350 | 12350 | 30000 | 69345 |

Table 6 provides information related to the profit expense proportion for mungbean cultivation. The gross return was perceived highest (79036.10 tk/ha) at treatment $T_3$ and the lowest (60885.00 tk/ha) gross return was observed at treatment $T_1$. From Table 6, it was illustrated that the benefit cost ratio was higher (1.14) at $T_3$ treatment.

Table 6. Benefit cost ratio of mungbean cultivation at IWMD research field, Gazipur

| Treatment | Total Cost (tk/ha) | Gross Return (tk/ha) | BCR | Yield (kg/ha) |
|---|---|---|---|---|
| $T_1$ | 56995.00 | 60885.00 | 1.07 | 1029.00 |
| $T_2$ | 63170.00 | 66907.75 | 1.06 | 1029.35 |
| $T_3$ | 69345.00 | 79036.10 | 1.14 | 1215.94 |
| $T_4$ | 69345.00 | 67325.05 | 0.97 | 1035.77 |

In case of RARS research field, some unlike situation was observed from Table 7. The cultivation cost was similar as the IWMD research field but Table 7 illustrated some unlike situation in case of BCR than IWMD research field. The highest (1.34) BCR was perceived at $T_3$ treatment and the lowest (1.23) BCR was observed at $T_1$ treatment. In case of RARS, Barishal research field the $T_3$ treatment gave higher production than IWMD research field in Gazipur.

Table 7. Benefit cost ratio of mungbean cultivation at RARS, Rahmatpur, Barishal research field

| Treatment | Total Cost (tk/ha) | Gross Return (tk/ha) | BCR | Yield (kg/ha) |
|---|---|---|---|---|
| $T_1$ | 56995 | 70048.55 | 1.23 | 1077.67 |
| $T_2$ | 63170 | 78736.45 | 1.25 | 1211.33 |
| $T_3$ | 69345 | 93253.55 | 1.34 | 1434.67 |
| $T_4$ | 69345 | 81683.55 | 1.18 | 1256.67 |

## Conclusion

Irrigation at mungbean cultivation have positive effect which increases yield largely. But in some weather perspective irrigation may effect profit. In case of southern farmers two irrigation (early vegetative stage and flowering stage) can enhance mungbean production. Another year research performance will specify the relations of different irrigation levels on BARI mug-8 cultivation at both Gazipur and Barishal.

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# OPTIMIZE FERTIGATION MANAGEMENT TO MINIMIZE NITRATE LEACHING FROM DRIP IRRIGATED BRINJAL FIELD

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## Abstract

This research was carried out at the research field of Irrigation and water Management Division (IWM) of Bangladesh Agricultural Research Institute (BARI), Gazipur during 2019-2020, 2020-2021, and 2021-2022 to optimize fertigation management for minimizing nitrate leaching from drip irrigated brinjal field. BARI Bt. Brinjal 4 cultivar was used for the experiment. There were four different irrigation treatments comprising two levels of irrigation intervals and two irrigation timings [Drip irrigation at 4-day interval with fertigation at the beginning of the irrigation cycle ($T_1$), Drip irrigation at 3-day interval with fertigation at the beginning of the irrigation cycle ($T_2$), Drip irrigation at 4-day interval with fertigation at the end of the irrigation cycle ($T_3$), and Drip irrigation at 3-day interval with fertigation at the end of the irrigation cycle ($T_4$)]. It is observed that yield and yield contributing characters were varied significantly among the irrigation treatments for the three growing seasons and that yield components followed the similar trend. It is also observed that treatment $T_4$ received highest amount of irrigation (270 mm) followed by the treatments $T_2$, $T_3$, and $T_1$ in 2019-2020 growing season. Although the treatments received different amounts of irrigation water in the growing seasons 2020-2021 and 2021-2022, the trend of water application remained the same. Modelling results for optimizing fertigation management is being conducted and will be presented in the final version of the report.

## Introduction

Groundwater pollution from use of nitrogenous fertilizer in intensive agriculture is becoming one of the major concerns in recent years. Appropriate management of nutrient and water in agricultural activities is the key to minimizing groundwater pollution and maximizing crop productivity (Abdelkhalik et al., 2019; Ajdary et al., 2007; Azad et al., 2018). Optimized management practices aiming at reducing the amount of water and nitrogen application without compromising with the yield reduction are able to reduce the extent of groundwater pollution through nitrate leaching (Shrestha et al., 2010). Based on the crop nitrogen requirement, this management strategy should incorporate soil moisture regulation for nitrate transport as well as managing the amount and timing of application of nitrogen fertilizers (Shrestha et al., 2010). Drip fertigation is a promising irrigation technology, which improves water and nutrient use efficiency to enhance crop productivity. If designed and managed properly, drip fertigation is likely to maximize nutrients uptake by plants and minimize water and solute losses beyond the root zone of the plants. However, optimization strategy of fertigation management plays an important role in the implementation of drip fertigation in order to obtain better crop yields and reduced soil and groundwater contamination. Therefore, the main objective of this study is to develop a drip fertigation management strategy that includes supplying adequate nitrogen to brinjal crop, minimizing nitrate leaching to groundwater, and avoiding nitrogen accumulation in the soil at the end of the crop growing season.

Development of any management strategy requires evaluation of several scenarios through optimization approach. These scenarios are very difficult, if not impossible to obtain from the field experimental setup. A simulation model is often employed to generate different scenarios using a particular set of data obtained from the field. Many simulation models have been implemented to simulate water flow and solute transport in soil, among which HYDRUS-1D and HYDRUS (2D/3D) (Simunek et al. 2011) has been extensively used because of its ability to incorporate root distribution as well as water and nutrient uptake by the crop. Present study intended to utilize HYDRUS (2D/3D) simulation to generate various scenarios of drip fertigation management and the corresponding nitrate

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concentration in the root zone water and beyond the root zone. Therefore, the objective of this study was to optimize drip fertigation management to minimize nitrate leaching.

## Materials and Methods

The field experiment was conducted during the rabi season of 2019-2020 (Year-1) and 2020-2021 (Year-2), between the months of December and April, at the research field of Irrigation and Water Management Division (IWM), Bangladesh Agricultural Research Institute (BARI), Gazipur. The experimental field was located between 24.00$^o$ N latitude and 90.25$^o$E longitude with an altitude of 8.40 m above MSL. The sand, silt and clay proportions of the soil in the experimental field were 36.5, 35.4 and 28.1, respectively. Top 30 cm of the soil layer had a field capacity, wilting point and bulk density values of 28.5%, 13.72% and 1.46 g cm$^{-3}$, respectively. The nutrient content of the experimental soil in the form of N, $P_2O_5$ and $K_2O$ were 51.1, 12.5 and 265.6 kg ha$^{-1}$, respectively while the organic matter content of the top soil was recorded as 1.04%.

BARI Bt. Brinjal 4 cultivar was used for the study. The experiment was laid out in a randomized complete block design with four drip fertigation treatments replicated thrice. The treatments were as follows:

$T_1$ = Drip irrigation at 4-day interval with fertigation at the beginning of the irrigation cycle
$T_2$ = Drip irrigation at 3-day interval with fertigation at the beginning of the irrigation cycle
$T_3$ = Drip irrigation at 4-day interval with fertigation at the end of the irrigation cycle
$T_4$ = Drip irrigation at 3-day interval with fertigation at the end of the irrigation cycle

The unit plot size was 5 m × 4 m. The experimental blocks were separated by 2 m and the plots within each block were separated by 1 m wide buffer strips in order to prevent lateral seepage of applied irrigation water into the adjacent plots. Brinjal plants of 28 days old were transplanted on 08 December 2019 with a plant spacing of 100 × 75 cm. Farm yard manure at the rate of 10 t ha$^{-1}$ was properly mixed with the soil during the land preparation. Fertilizers were applied at the rate of 375 kg N, 250 kg P, 250 kg K, and 100 kg gypsum per hectare. Half of the nitrogen and phosphorus, and the full doses of potassium and gypsum were applied during the land preparation while the remaining half of the nitrogen and phosphorus was applied with drip fertigation.

### *Estimation of irrigation water*

The irrigation water was applied to bring the soil moisture at field capacity considering effective root zone depth. Soil moisture was determined before each irrigation by gravimetric method. Irrigation was applied up to the field capacity of the soil. Measured amount water was applied to all treatments in ring basin method.

The normal depth of water needed to apply was determined using the following equation:

$$d = \frac{FC - MC_i}{100} \times A_s \times D \quad (1)$$

where, $d$ = depth of irrigation, mm; $FC$ = field capacity of the soil, %; $MC_i$ = moisture content of the soil at the time of irrigation, %; $A_s$ = apparent specific gravity of the soil; $D$ = root zone depth, mm.

Rainfall data were collected from the weather station, Joydebpur, Gazipur. Effective rainfall was calculated on daily basis during the growing period.

### *Water Productivity Index (WPI)*

Water productivity index was calculated using the following equation:

$$WPI = Y/q \quad (2)$$

where, $WPI$ = Water Productivity Index, kg/m$^3$; $Y$ = the yield (kg/ha) for the season in the specific area; $q$ = total supply of water including rainfall per ha for the season in the specific area, m$^3$/ha.

**Statistical analysis**

Statistical analysis was carried out to obtain the variance for different parameters. Treatment effects were analyzed using a one-way ANOVA using MATLAB.

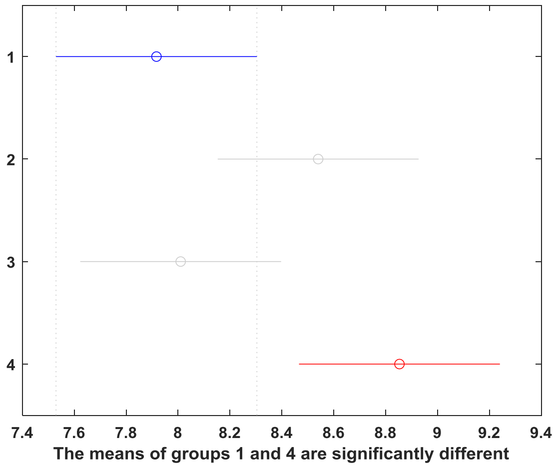
## Results and Discussion

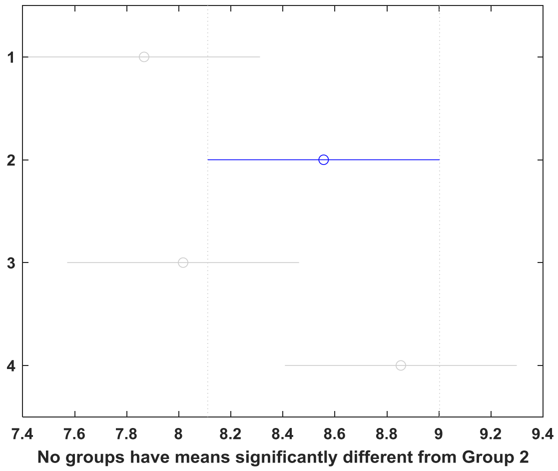
Yield and yield contributing characters of brinjal during 2019-2020 (Year-1), 2020-2021 (Year-2), and 2021-2022 (Year-3) growing seasons were analyzed statistically and are presented in Table-1. It is observed from Table-1 that irrigation treatments had significant effects on all the yield and yield contributing characters of brinjal. In 2019-2020 (Year-1), the highest marketable yield was obtained from treatment $T_4$ (32.91 t/ha) followed by the treatments $T_2$ (32.64 t/ha), $T_3$ (31.84 t/ha), and $T_1$ (31.29 t/ha). Similarly, the highest (37.24 t/ha) and lowest (31.41 t/ha) marketable yields were obtained from treatments $T_4$ and $T_1$, respectively in the second year (Year-3). The marketable yield of brinjal followed the similar trend during the third year (Year-3). The highest marketable yield of 36.76 t/ha was obtained from the treatment $T_4$ while the lowest marketable yield was obtained from the treatment $T_1$ (31.32 t/ha) Therefore, it is perceived that despite varied in magnitude, the marketable yield of brinjal followed the similar trend during the three growing seasons as evidenced from the results presented in Table 1.

Table 1. Yield and yield contributing characters of brinjal during 2019-2020 growing season

| Treatments | Length of fruit, cm | Diameter of fruit, cm | Unit weight of fruit, g | Cull yield, t/ha | Marketable yield, t/ha |
|---|---|---|---|---|---|
| **Year-1 (2019-2020** | | | | | |
| $T_1$ | 7.92 | 6.45 | 425 | 8.71 | 31.29 |
| $T_2$ | 8.54 | 7.25 | 450 | 7.36 | 32.64 |
| $T_3$ | 8.01 | 5.92 | 432 | 8.16 | 31.84 |
| $T_4$ | 8.85 | 7.93 | 438 | 7.09 | 32.91 |
| F | 6.74 | 27.35 | 141.14 | 17.18 | 47.08 |
| Prob.>F | 0.014 | 0.0001 | $2.88\times10^{-7}$ | 0.0008 | $1.98\times10^{-5}$ |
| **Year-2 (2020-2021)** | | | | | |
| $T_1$ | 7.87 | 6.52 | 428 | 8.69 | 31.41 |
| $T_2$ | 8.56 | 7.21 | 455 | 7.42 | 32.71 |
| $T_3$ | 8.02 | 5.87 | 437 | 8.11 | 31.97 |
| $T_4$ | 8.85 | 7.97 | 442 | 7.08 | 33.01 |
| F | 5.49 | 25.79 | 44.48 | 83.89 | 37.24 |
| Prob.>F | 0.0241 | 0.0002 | $2.46\times10^{-5}$ | $2.19\times10^{-6}$ | $4.77\times10^{-5}$ |
| **Year-3 (2021-2022)** | | | | | |
| $T_1$ | 7.93 | 6.43 | 423 | 8.59 | 31.32 |
| $T_2$ | 8.61 | 7.29 | 461 | 7.39 | 32.83 |
| $T_3$ | 8.11 | 6.01 | 444 | 8.03 | 32.08 |
| $T_4$ | 8.89 | 7.95 | 471 | 6.99 | 33.11 |
| F | 5.31 | 21.54 | 31.06 | 43.68 | 36.76 |
| Prob.>F | 0.0262 | 0.0003 | $9.313\times10^{-5}$ | $2.634\times10^{-5}$ | $50..9\times10^{-5}$ |

Multiple comparison tests were performed to determine which treatments were different than the others in terms of yield and yield attributing characters of brinjal. Multiple comparison test for the treatments in terms of the length of fruit of brinjal for the three growing seasons (2019-2020, 2020-2021, and 2021-2022) is presented in Figure 1. The multiple comparison test for the three growing seasons (2019-2020, 2020-2021, and 2021-2022) suggested that the means of groups 1 and 4 were significantly different (2019-2020); no groups had means significantly different from group 2 (2020-2021); the means of groups 1 and 4 were significantly different than others (2021-2022).




**(a)**

**(c)**

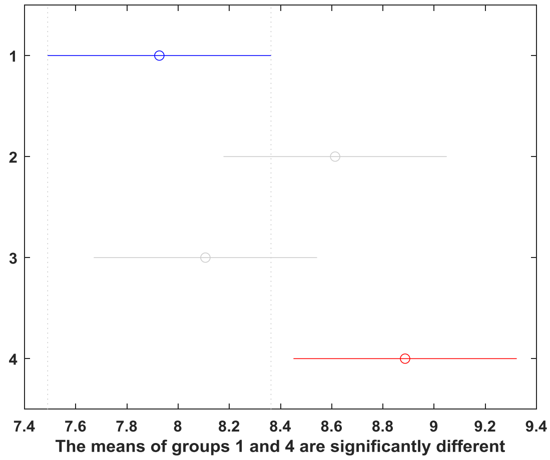
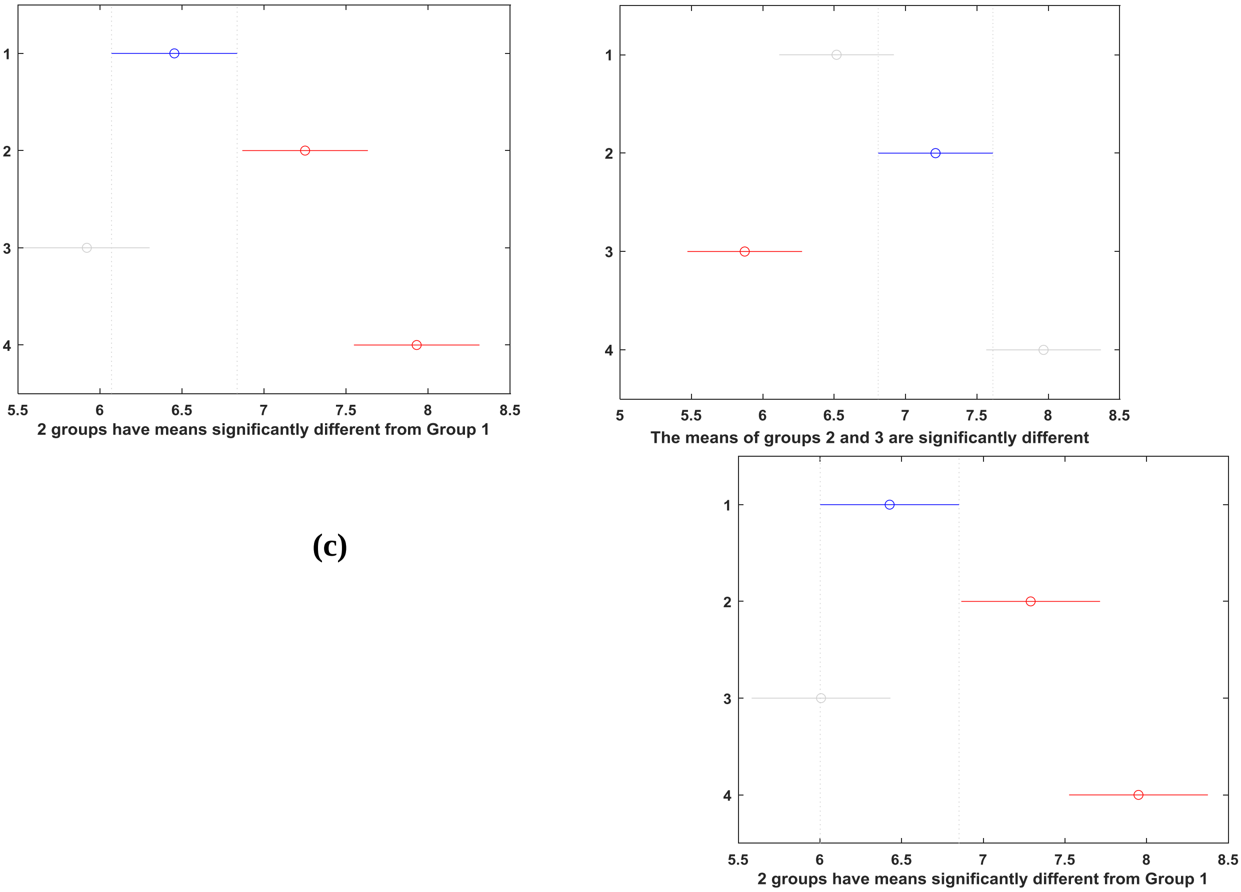



Figure 1. Multiple comparison test for the treatments in terms of the length of fruit: (a) 2019-2020, (b) 2020-2021, and (c) 2021-2022.

For the diameter of fruits, the multiple comparison test showed the similar trends for the three growing seasons. The multiple comparison test for different treatments (presented in Figure 2) revealed that two groups (group 2 and 4) had means significantly different from group 1 (2019-2020); the means of two groups (group 2 and 3) had means significantly different from the groups 1 and 4 (2020-2021); two groups (group 2 and 4) had means significantly different from group 1 (2021-2022).

(a)




(c)

Figure 2. Multiple comparison test for the treatments in terms of the diameter of fruit: (a) 2019-2020, (b) 2020-2021, and (c) 2021-2022.

Multiple comparison test for the treatments in terms of the unit weight of fruit of brinjal for the growing season 2019-2020 is presented in Figure 3 (a), which suggested that three groups (groups 2, 3, 4) had means significantly different from group 1; three groups (groups 1, 3, 4) had means significantly different from group 2; three groups (groups 1, 2, 4) had means significantly different from group 3; and three groups (groups 1, 2, 3) had means significantly different from group 4. Results for the growing season 2020-2021 are presented in Figure 3 (b), which indicates that two groups (groups 2 and 4) have means significantly different from group 1; two groups (group 1 and 3) have means significantly different from group 2; two groups (groups (2 and 4) have means significantly different from group 3; and two groups (group 1 and 3) have means significantly different from group 4. Multiple comparison results for the growing season 2021-2022 are presented in Figure 3 (c) which indicate that three groups (groups 2, 3, and 4) had means significantly different from group 1.

(a)

(c)

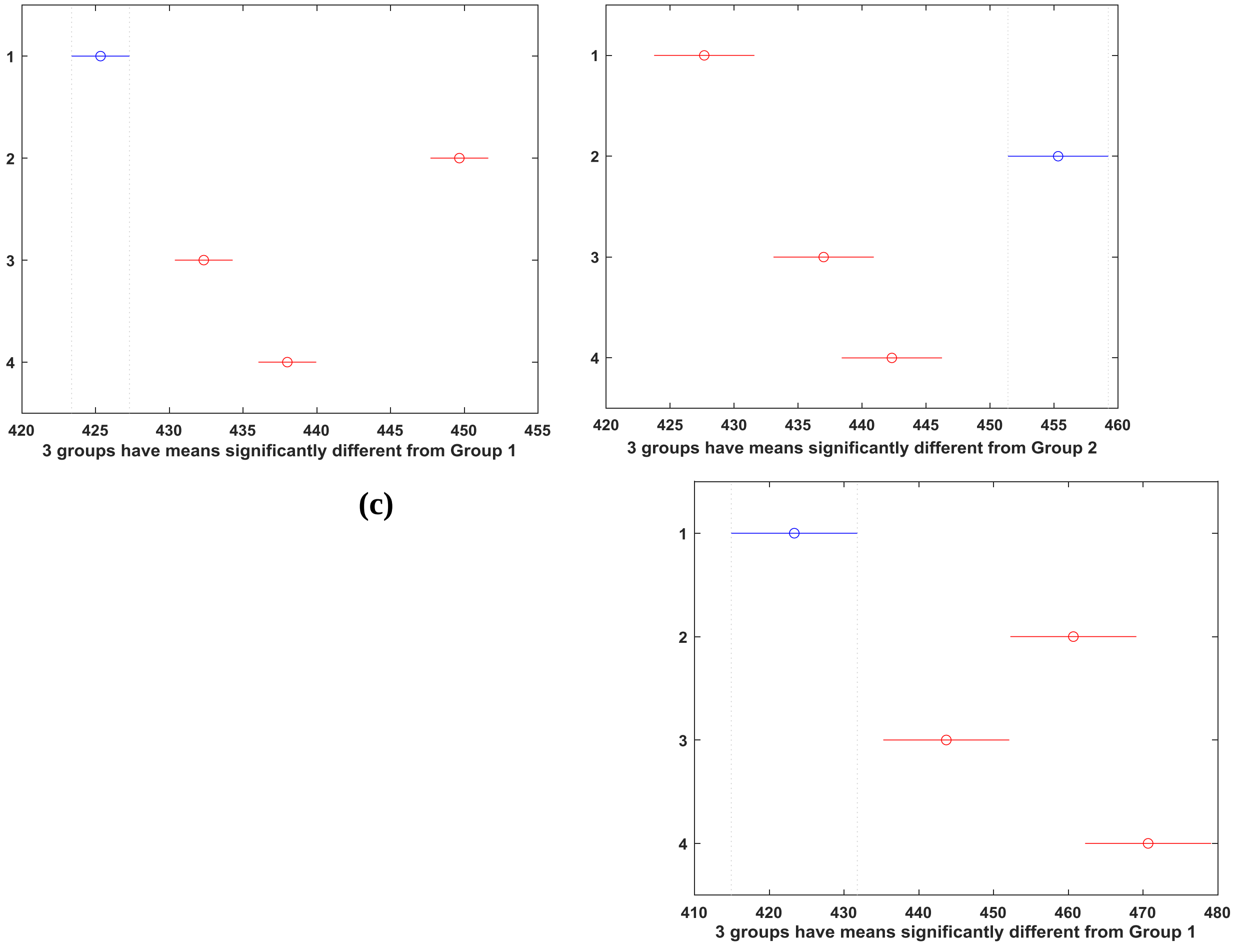
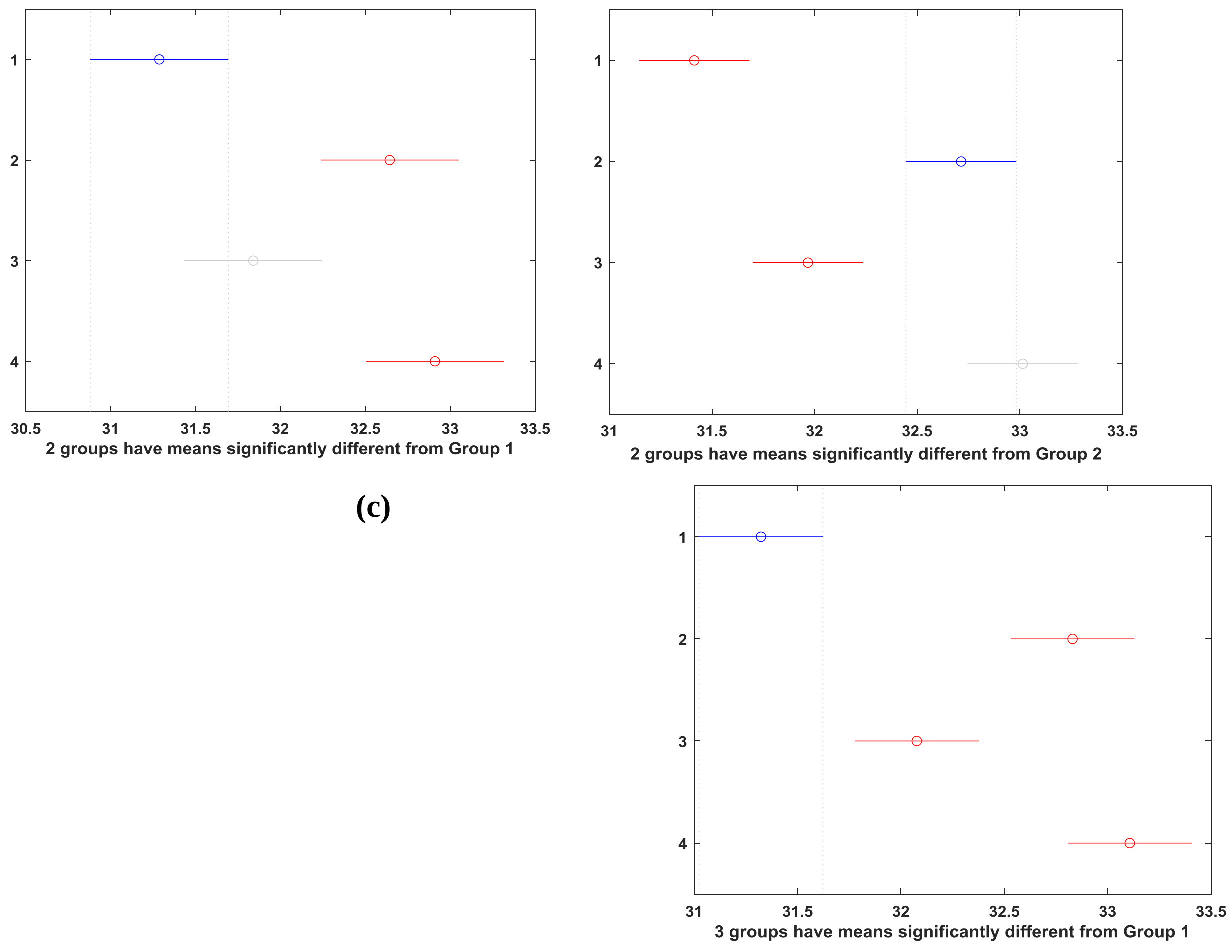



Figure 3. Multiple comparison test for the treatments in terms of the unit weight of fruit: (a) 2019-2020, (b) 2020-2021, and (c) 2021-2022.

Treatment variations for the marketable yield obtained from the multiple comparison test for the growing season 2019-2020 are presented in Figure 4 (a). It was observed from Figure 4 (a) that two groups (groups 2 and 4) had means significantly different from group 1; the means of groups 2 and 1 were significantly different; the means of groups 3 and 4 were significantly different; two groups (groups 1 and 3) had means significantly different from group 4. Results of multiple comparison test for the growing season 2020-2021 is illustrated in Figure 4 (b), which revealed the similar trend as in case of multiple comparison tests for the growing season 2019-2020. Results of multiple comparison test for the growing season 2021-2022 revealed that three groups (groups 2, 3, and 4) had means significantly different from group 1.

**(a)**




**(c)**

Figure 4. Multiple comparison test for the treatments in terms of marketable yield: (a) 2019-2020, (b) 2020-2021, and (c) 2021-2022.

Multiple comparison test for the treatments in terms of the cull yield of brinjal for the two growing seasons is presented in Figure 5, which suggested that, for both growing seasons (2019-2020 and 2020-2021), three groups (groups 1, 2, 3) had means significantly different from group 1; two groups (groups 1 and 3) had means significantly different from group 2; three groups (groups 1, 2, 4) had means significantly different from group 3; and two groups (groups 1 and 3) had means significantly different from group 4. Results for the growing season 2021-2022 suggested that three groups (groups 2, 3, and 4) had means significantly different from group 1.

(a)

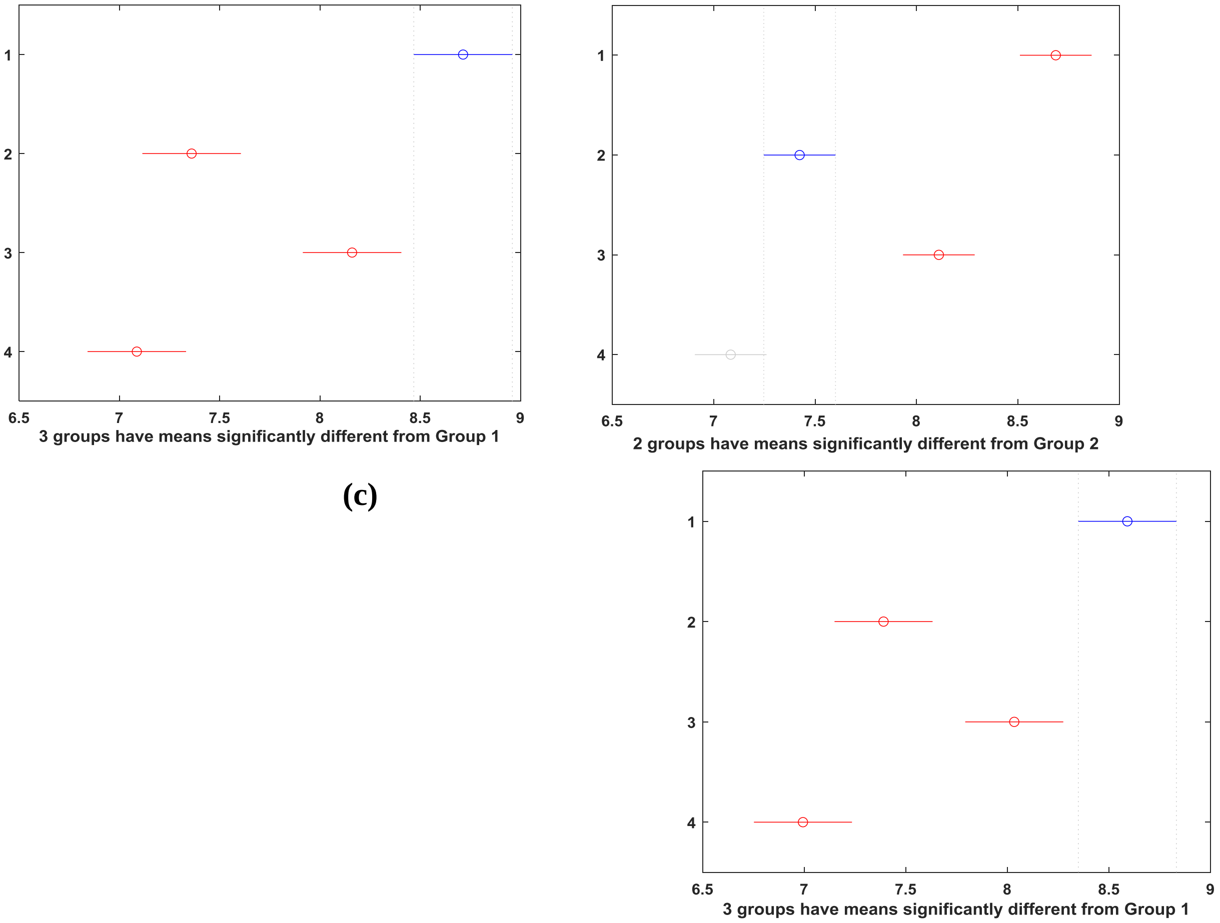



Figure 5. Multiple comparison test for the treatments in terms of cull yield: (a) 2019-2020, (b) 2020-2021, and (c) 2021-2022.

***Seasonal water use and water productivity***

In growing season 2019-2020, treatments $T_1$ and $T_3$ received 23 numbers of irrigation events whereas treatments $T_2$ and $T_4$ received a total number of 31 irrigations. On the other hand, treatments $T_1$ and $T_3$ received 26 numbers of irrigation events whereas treatments $T_2$ and $T_4$ received a total number of 32 irrigations in the growing season 2020-2021. In 2021-2022 growing season, treatments $T_1$ and $T_3$ received 25 numbers of irrigation events whereas treatments $T_2$ and $T_4$ received a total number of 29 irrigations. The irrigation events were accomplished based on the design of the experiment. In 2019-2020, treatment $T_4$ received highest amount of irrigation (270 mm) followed by the treatments $T_2$, $T_3$, and $T_1$. Effective rainfall for the crop growing period was calculated as 223 mm (80% of total rainfall). Likewise, in 2020-2021, the highest (276 mm) and lowest (202 mm) amounts of irrigation water was received by treatments $T_4$ and $T_1$, respectively. The effective rainfall during the crop growing period of 2020-2021 was estimated to be 112 mm. On the other hand, for the growing season 2021-2022, treatment $T_4$ received highest amount of irrigation (271 mm) followed by the treatments $T_2$, $T_3$, and $T_1$ (263 mm, 207 mm, and 197 mm). Effective rainfall for the crop growing period was calculated as 205 mm (80% of total rainfall). Water used by the plants in different treatments during growing seasons is shown in Table-2.

Table-2. Water use and water productivity of brinjal in different treatments

| Treatments | Amount of irrigation water, mm | Effective rainfall, mm | Soil water contribution, mm | Seasonal water use, mm | Yield, t/ha | Water productivity, kg/m$^3$ |
|---|---|---|---|---|---|---|
| **Year-1 (2019-2020)** | | | | | | |
| $T_1$ | 195 | 223 | 18.92 | 436.92 | 31.29 | 7.16 |
| $T_2$ | 260 | 223 | 12.55 | 495.55 | 32.64 | 6.59 |
| $T_3$ | 202 | 223 | 24.33 | 449.33 | 31.84 | 7.09 |
| $T_4$ | 270 | 223 | 28.18 | 521.18 | 32.91 | 6.31 |
| **Year -2 (2020-2021)** | | | | | | |
| $T_1$ | 202 | 112 | 16.83 | 330.83 | 31.41 | 9.49 |
| $T_2$ | 268 | 112 | 11.41 | 391.41 | 32.71 | 8.36 |
| $T_3$ | 208 | 112 | 20.34 | 340.34 | 31.97 | 9.39 |
| $T_4$ | 276 | 112 | 24.13 | 412.13 | 33.01 | 8.01 |
| **Year -3 (2021-2022)** | | | | | | |
| $T_1$ | 197 | 205 | 17.92 | 419.92 | 31.32 | 7.46 |
| $T_2$ | 263 | 205 | 12.11 | 480.11 | 32.83 | 6.84 |
| $T_3$ | 207 | 205 | 21.23 | 433.23 | 32.08 | 7.40 |
| $T_4$ | 271 | 205 | 25.17 | 501.17 | 33.11 | 6.61 |

## Conclusion

The findings of the growing seasons 2019-2020, 2020-2021, and 2021-2022 revealed a similar pattern of yield response, yield attributing characters, and seasonal crop water use. At least three yeas' data will be required to develop modelling of nitrate leaching. Therefore, for obtaining a definite conclusion regarding the yield response and nitrate leaching, the modelling works using HYDRUS is being conducted. The modelling results will be presented in the final version of the report.

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## DAILY AND MULTI-STEP AHEAD FORECASTING OF POTENTIAL EVAPOTRANSPIRATION USING MACHINE LEARNING ALGORITHMS WITH LIMITED CLIMATIC DATA

D.K. ROY[1], S.K. BISWAS[2] AND M.A. HOSSAIN[3]

### Abstract

Accurate prediction of potential evapotranspiration ($ET_0$) is essential for efficient planning and management of limited water resources through judicial irrigation scheduling. The FAO-56 Penman-Monteith (FAO-56 PM) approach to $ET_0$ estimation was adopted to compute $ET_0$ from data obtained during the period 2004–2019 from a weather station located in Gazipur Sadar Upazilla, Bangladesh. The obtained meteorological variables (e.g., daily maximum and minimum temperatures, wind speed, relative humidity, and sunshine duration) and computed $ET_0$ values were used as inputs and outputs, respectively, for modelling daily and multi-step ahead $ET_0$ predictions. Based on the previous years' finding, LSTM and Bi-LSTM models were found to be the best performer over others (other machine learning based models) for daily and one-step ahead $ET_0$ predictions, respectively. In this effort, the generalization capability of the developed best models developed at Gazipur station was evaluated on a new unseen data (from 01 January to 30 April 2022) obtained from a test station, Barishal. Moreover, the developed $ET_0$ model using the data from 01 January 2004 to 30 June 2019 at Gazipur station was further tested at the same station with the new dataset spanning over 01 July 2019 to 30 April 2022. The model performance was evaluated on several statistical performance evaluation indices computed on the FAO-56 PM estimated and model predicted daily $ET_0$ values. The generalization results revealed that, for the daily prediction, the LSTM performed equally well as with the training station (Gazipur) dataset, for which the models were developed. The daily $ET_0$ prediction using the Barishal dataset provided higher values of R, NS, and IOA (R = 0.909, NS = 0.559, IOA = 0.904) as well as lower values of RMSE, NRMSE, MAD, and MAE (RMSE = 0.687 mm $d^{-1}$, NRMSE = 0.214, MAD = 0.229 mm $d^{-1}$, MAE = 0.618 mm $d^{-1}$) indicating an outstanding generalization capability of the LSTM model developed at Gazipur station. On the other hand, the developed LSTM model produced RMSE, NRMSE, R, MAD, MAE, NS, and IOA values of 0.596 mm $d^{-1}$, 0.1714, .0887, 0.219 mm $d^{-1}$, 0.459 mm $d^{-1}$, 0.719, and 0.933, respectively for the recent new dataset from the Gazipur station, for which the model was not developed. In addition, multi-step ahead forecasting was performed using the Barishal data based on time-lagged information obtained through the partial autocorrelation functions of the $ET_0$ time series. Results revealed that although the forecasting performance decreases with the increases in the forecasting horizon, the Bi-LSTM model produced acceptable values of performance evaluation indices (higher values of the benefit indices: R, NS, IOA and lower values of the cost indices: RMSE, NRMSE, MAD, MAE). Hence, both models showed very good performance for both daily and multi-step (5-day ahead) predictions as indicated by the computed performance evaluation indices. The findings of this research demonstrated the ability of the developed deep learning model (LSTM) to generalize the prediction capabilities outside the training station. Multi-step ahead forecasting results revealed the practical applicability of the proposed Bi-LSTM model in forecasting days ahead $ET_0$ values.

### Introduction

Agriculture is considered to be the largest consumer of global freshwater reserves. Therefore, a careful and judicious management of irrigation practices would allow significant water savings. To achieve this water saving, an accurate estimation of the evapotranspiration (ET) is required, which is regarded as one of the major components of water balance. ET plays an important role in surface energy and water budgets, and is an important parameter in the interactions between vegetation, soil, and the atmosphere (Liu et al., 2013). Accordingly, proper management of water resources in irrigated agriculture is largely dependent on an accurate estimation of this vital component of the hydrologic cycle. In general, precise quantification of ET aids in the design and management of efficient irrigation systems, simulation of crop yields, determination of the hydrologic water balance, along with the planning and allocation of water resources (Kisi, 2016). ET can be measured directly by

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experimental techniques such as the Bowen ratio energy balance method, lysimeter approaches, or eddy covariance systems (Kool et al., 2014) or estimated by computing potential or reference evapotranspiration ($ET_0$) from meteorological variables. As direct methods of ET measurement are costly, complex and largely unavailable in many regions (Allen et al., 1998; Ding et al., 2013), indirect methods based on $ET_0$ estimation have become popular in many regions where direct experimental techniques are not available. The FAO-56 Penman-Monteith (FAO-56 PM) model is recommended by the United Nations' Food and Agriculture Organization (FAO) as the standard reference method for estimating $ET_0$ and validating other methods (Allen et al., 1998). The FAO-56 PM method having been recognized as a universal approach to $ET_0$ estimation, this method can be used in a wide range of environmental and climatic conditions without the requirement of any local calibration. This well-established method has been validated using lysimeters under a range of different climatic conditions (Landeras et al., 2008). Since $ET_0$ is solely affected by meteorological conditions, it can be calculated using the FAO-56 PM method by drawing upon several meteorological variables (e.g., relative humidity, wind speed, solar radiation, and minimum/maximum air temperatures. Once the $ET_0$ is estimated, the actual evapotranspiration ($ET_a$) can be calculated by means of the $ET_0$ and crop coefficients.

In recent years, Artificial Intelligence (AI) models have been successfully applied to the modelling of $ET_0$ in different hydrologic regions. Artificial Neural Networks (ANN) were the first AI models implemented to estimate $ET_0$ (Kumar et al., 2002). Other applications of AI models in estimating $ET_0$ includes the use of Random Forests (RF) (Feng et al., 2017; Huang et al., 2019), Generalized Regression Neural Networks (GRNN) (Feng et al., 2017), Extreme Learning Machine (ELM) (Dou and Yang, 2018), Support Vector Machine (SVM) (Ferreira et al., 2019; Huang et al., 2019), Genetic Programming (GP) (Gocić et al., 2015), Gaussian Process Regression (GPR) (Karbasi, 2018), Multivariate Adaptive Regression Splines (MARS) (Kisi, 2016), M5 Model Tree (M5Tree) (Kisi, 2016), Gene-Expression Programming (GEP) (Gavili et al., 2018; Shiri et al., 2014; Wang et al., 2019), and Adaptive Neuro Fuzzy Inference System (ANFIS) (Dou and Yang, 2018; Gavili et al., 2018).

Deep learning (DL) has recently been recognized as a developed and sophisticated sub-domain of machine learning techniques in the arena of artificial intelligence. The DL-based modelling has gained popularity in the successful application to various domain of science including language processing (Plappert et al., 2018), image classification (Fan et al., 2019), computer vision (Fang et al., 2019), speech recognition (Cummins et al., 2018), and time series prediction (Tien Bui et al., 2020). The usage of DL has also been observed in developing prediction models in the research niche of groundwater level forecasting (Supreetha et al., 2020), and prediction of short-term water quality variable (Barzegar et al., 2020). Recurrent Neural Network (RNN) models are able to preserve a memory of previous network states and are better suited for predicting groundwater levels through modelling time series of groundwater table data observed at an observation well. For this reason, numerous recent studies related to groundwater modelling (Guzman et al., 2017) have focused on the successful application of the RNNs. However, the standard RNN architectures cannot properly grab hold of the long-term reliance between variables (Bengio et al., 1994) due mainly to the occurrences of two problems: vanishing and exploding gradients. These are situations where the network weights either reach to zero or turn out to be enormously large during training of the network.

Long Short-Term Memory (LSTM) networks, a variant of typical RNN architectures, is capable of overcoming the training drawbacks (vanishing and exploding gradient problems) of RNNs through retaining valuable information for model development while avoiding unnecessary or redundant information being passed to the subsequent states in the model development process. LSTM has successfully been applied to the research arena of natural language processing, and financial time series prediction (Fischer and Krauss, 2018), traffic congestion and travelling period predictions (Zhao et al., 2017). In spite of wide applicability in various research domains, LSTM models has only recently been utilized for the forecast of hydrologic time series (Zhang et al., 2018). Recently, Jeong et al., (2020) applied LSTM-based modelling to estimate groundwater level using the corrupted data (with outliers and noise) and found that robust training of an LSTM model using a developed cost function ("least trimmed squares with asymmetric weighting and the Whittaker smoother") can adequately model noisy groundwater level data. The prediction ability of an LSTM network was found superior than that of a RNN in predicting hourly groundwater level values in a coastal city (susceptible to periodic flooding) of Norfolk, Virginia, USA. Mouatadid et al., (2019) used a coupled "maximum overlap discrete wavelet transformation" and LSTM for achieving precision and robustness in the forecasting of irrigation flow. Zhang et al., (2018) proposed an LSTM network for predicting depths in water table in agrarian areas and obtained an acceptable prediction result by utilizing simply an uncomplicated data pre-processing technique. Based on their findings, one can argue that an LSTM network does not require a massive data smoothing or pre-processing in producing an acceptable prediction accuracy. The integrated use of Gated Recurrent Unit and Convolutional Neural Network (CNN-GRU) can also be found in recent literature (Pan et al., 2020) for developing water level prediction models in which CNN-GRU outperformed an LSTM model with regard to Nash-Sutcliffe (NS) Efficiency Coefficient, Average Relative Error, and Root Mean Squared Error. The prediction accuracy of a lion algorithm optimized LSTM network was found superior than an ordinary LSTM network for the prediction of groundwater level using the historical groundwater level data obtained from an observation well and rainfall data collected from a weather station located in the Udupi district, India (Supreetha et al., 2020). To the best of the author's understanding, an LSTM network has not previously been used to predict daily and multi-step ahead $ET_0$ predictions especially in the Gazipur district of Bangladesh.

The key motivation and focus of this study were to: (1) assess the generalization capability of the proposed deep learning model (LSTM) to predict $ET_0$ at a nearby station, at which the models were neither trained or validated; and (2) provide multi-step (5-day ahead) ahead forecasting of $ET_0$ values using Bi-LSTM based deep learning model.

## Materials and Methods

Meteorological variables were acquired from two weather stations located in the Gazipur Sadar Upazila of the Gazipur district and Barishal station of the Barishal Division in Bangladesh. The weather station in Gazipur is situated between 24.00°N latitude and 90.43°S longitude with an altitude of 8.4 m above the mean sea level. Meteorological variables including solar radiation, relative humidity, minimum and maximum temperatures, and wind speed were obtained for 15.5 years (from 01 January 2004 to 30 June 2019). Descriptive statistics of the meteorological variables for the training station are given in Table 1. It is perceived from Table 1 that the climatological variables demonstrated left (negative) skewness which indicates that the distribution of data for all variables had an extended left tail than the right tail. Kurtosis, on the other hand, had both positive and negative values indicating that the datasets had both "heavy-tailed" (positive values of kurtosis) and "light-tailed" (negative values of kurtosis) distributions.

Table 1. Statistical metrices of climatological variables obtained from an automatic weather station located in Gazipur Sadar Upazilla, Bangladesh

| Variables | Mean | Standard deviation | Skewness | Kurtosis |
|---|---|---|---|---|
| Minimum temperature, °C | 21.17 | 5.64 | -0.63 | -0.88 |
| Maximum temperature, °C | 30.93 | 3.92 | -1.10 | 2.11 |
| Relative humidity, % | 80.22 | 8.20 | -0.63 | 0.75 |
| Wind speed, km/d | 241.15 | 90.69 | -0.06 | -1.32 |
| Sunshine duration, h | 5.54 | 3.09 | -0.40 | -1.04 |

The data for the test station were acquired from 01 January 2015 to 30 April 2022 (2677 daily entries of meteorological variables and computed daily $ET_0$). Descriptive statistics of the meteorological variables of the test station are presented in Table 2. It is perceived from Table 2 that the climatological variables demonstrated both left (negative) and right (positive) skewness which indicates that the distribution of data for minimum temperature, maximum temperature, relative humidity, and sunshine duration had an extended left tail than the right tail. On the other hand, positive skewness values for wind speed and $ET_0$ indicates an extended right tail than the left tail in the data distribution. Kurtosis, on the other hand, had both positive and negative values indicating that the datasets had both “heavy-tailed” (positive values of kurtosis) and “light-tailed” (negative values of kurtosis) distributions.

Table 2. Descriptive statistics of meteorological variables for the test station (Barishal station), Bangladesh

| Variables | Mean | Standard deviation | Skewness | Kurtosis |
|---|---|---|---|---|
| Minimum temperature, °C | 21.57 | 5.32 | -0.73 | -0.78 |
| Maximum temperature, °C | 30.42 | 3.91 | -0.58 | -0.03 |
| Relative humidity, % | 91.89 | 4.87 | -4.22 | 52.45 |
| Wind speed, km $d^{-1}$ | 197.11 | 93.63 | 0.69 | -1.00 |
| Sunshine duration, h | 5.70 | 2.75 | -0.72 | -0.52 |
| $ET_0$, mm $d^{-1}$ | 3.20 | 1.04 | 0.30 | -0.87 |

Table 3 presents the descriptive statistics of the meteorological variables for the recent data obtained from the Gazipur station to test the generalization capability of the developed LSTM model. It is observed from Table 3 that the skewness has both positive and negative values indicating the data distribution had both extended right and left tails. Kurtosis, on the other hand, had both positive and negative values indicating that the datasets had both “heavy-tailed” (positive values of kurtosis) and “light-tailed” (negative values of kurtosis) distributions.

Table 3. Descriptive statistics of meteorological variables for the new dataset (from 01 July 2019 to 30 April 2022) of the Gazipur station

| Variables | Mean | Standard deviation | Skewness | Kurtosis |
|---|---|---|---|---|
| Minimum temperature, °C | 21.37 | 5.51 | -0.55 | -1.01 |
| Maximum temperature, °C | 31.21 | 4.09 | -0.92 | 0.62 |
| Relative humidity, % | 84.08 | 7.70 | -0.71 | 0.10 |
| Wind speed, km $d^{-1}$ | 123.32 | 19.45 | 0.02 | 0.16 |
| Sunshine duration, h | 5.94 | 3.00 | -0.55 | -0.86 |
| $ET_0$, mm $d^{-1}$ | 3.48 | 1.12 | 0.19 | -0.79 |

Meteorological variables obtained from the study areas across the period of study were utilized to estimate daily $ET_0$ by employing the FAO 56 PM equation. These computed daily values of $ET_0$ and the meteorological variables were used as outputs and inputs, respectively for the proposed HFS and other models. This indirect approach of $ET_0$ estimation from meteorological variables has been widely accepted in circumstances when $ET_0$ values are extremely hard to acquire directly (Allen et al. 1998; Shiri et al. 2014). The FAO 56 PM equation is represented by:

$$\mathrm{ET_0} = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T_{\mathrm{mean}} + 273} u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{1}$$

where, $\mathrm{ET_0}$ represents reference evapotranspiration, $\mathrm{mm\,d^{-1}}$; $\mathrm{R_n}$ is the net radiation at the crop surface, $\mathrm{MJ\,m^{-2}d^{-1}}$; G is the heat flux density of soil, $\mathrm{MJ\,m^{-2}d^{-1}}$ ; $\Delta$ is the slope of the saturation vapor pressure curve, $\mathrm{kP_a°C^{-1}}$; $\gamma$ is the psychometric constant, $\mathrm{kP_a°C^{-1}}$; $\mathrm{e_s}$ is the saturation vapor pressure, $\mathrm{kP_a}$; $\mathrm{e_a}$ is the actual vapor pressure, $\mathrm{kP_a}$; $\mathrm{u_2}$ is the wind speed at a height of 2 m, $\mathrm{m\,s^{-1}}$; and $\mathrm{T_{mean}}$ is the mean air temperature at 2.0 m height, °C.

### Statistical indices for performance evaluation

To assess the performance of the FT-based $ET_0$ models, several performance indicators were used in this study as follows:

RMSE:

$$RMSE = \frac{\sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(ET_{0_i}^{A} - ET_{0_i}^{P}\right)^2}}{\overline{ET_0{}^A}} \quad (2)$$

Normalized RMSE (Hyndman and Koehler, 2006):

$$NRMSE = \frac{RMSE}{\overline{ET_0{}^A}} \quad (3)$$

Mean Absolute Error (MAE):

$$MAE = \text{mean}\left[\left|ET_{0_i}^{A} - ET_{0_i}^{P}\right|\right] \quad (4)$$

Median Absolute Deviation (MAD):

$$MAD\left(ET_{0_i}^{A}, ET_{0_i}^{P}\right) = median\left(\left|ET_{0_1}^{A} - ET_{0_1}^{P}\right|, \left|ET_{0_2}^{A} - ET_{0_2}^{P}\right|, \ldots, \left|ET_{0_n}^{A} - ET_{0_n}^{P}\right|\right)$$
$$for\ i = 1, 2, \ldots, n \quad (5)$$

Nash-Sutcliffe Efficiency Coefficient (NS) (Nash and Sutcliffe, 1970):

$$NS = 1 - \frac{\sum_{i=1}^{n}\left(ET_{0_i}^{A} - ET_{0_i}^{P}\right)^2}{\sum_{i=1}^{n}\left(ET_{0_i}^{A} - \overline{ET_0{}^A}\right)^2} \quad (6)$$

Willmott’s Index of Agreement (IOA) (Willmott, 1981):

$$d = 1 - \frac{\sum_{i=1}^{n}\left(ET_{0_i}^{A} - ET_{0_i}^{P}\right)^2}{\sum_{i=1}^{n}\left(\left|ET_{0_i}^{P} - \overline{ET_0{}^A}\right|\left|ET_{0_i}^{A} - \overline{ET_0{}^A}\right|\right)^2} \quad (7)$$

Correlation Coefficient (R) (Kirch, 2008):

$$R = \frac{\sum_{i=1}^{n}\left(ET_{0_i}^{A} - \overline{ET_0{}^A}\right)\left(ET_{0_i}^{A} - \overline{ET_0{}^P}\right)}{\sqrt{\sum_{i=1}^{n}\left(ET_{0_i}^{A} - \overline{ET_0{}^A}\right)^2}\sqrt{\sum_{i=1}^{n}\left(ET_{0_i}^{P} - \overline{ET_0{}^P}\right)^2}} \quad (8)$$

where, $ET_{0_i}^{A}$ and $ET_{0_i}^{P}$ are the actual and model-predicted $ET_0$ for the $i^{th}$ points of data in the dataset, respectively; $\overline{ET_0{}^A}$ and $\overline{ET_0{}^P}$ are the average values of the actual and model-predicted $ET_0$, respectively; $n$ represents the total number of points in the set of data.

Generally, the RMSE criterion measures the error of the model. The lower value of RMSE indicates the higher prediction power of the model. However, the value of RMSE largely depends on the magnitude of the data, and therefore, a lower value of RMSE does not necessarily mean better prediction performance. To overcome this issue, the NRMSE criterion was used to eliminate the dimensionality effect of the data. The performance of a model is regarded as excellent when the value of NRMSE is lower than 0.1, good when NRMSE ranges between 0.1 and 0.2, fair when NRMSE falls between 0.2 and 0.3, poor when the NRMSE value is higher than 0.3 (Heinemann et al., 2012; Li et al., 2013). The correlation coefficient, R, denotes the strength of linear regression between actual and model-predicted daily $ET_0$; however, for this linear relationship, the highest possible value (ideal) of R = 1.0 can be obtained despite the slope and ordinate intercept being poles apart from 1.0 and zero, respectively (Barzegar et al., 2019). Therefore, other indices need to be used to justify the model performance. The aforementioned performance indices provide linear agreements between actual and predicted values and can be highly sensitive to outliers in the actual data while being equally sensitive to the proportional or additive difference between observations and predictions (Willmott, 1981). To overcome these limitations, NS and Willmott's IOA criteria were also used. A normalized/dimensionless measure of residual variance, the NS metric is calculated by dividing residual variance by the variance of an actual data set. $NS \leq 0.4$, $0.40 < NS \leq 0.50$, $0.50 < NS \leq 0.65$, $0.65 < NS \leq 0.75$, and $0.75 < NS \leq 1.00$ are classifications written off as unsatisfactory, acceptable, satisfactory, good, and exceptionally good, respectively (Gupta et al., 1999; Moriasi et al., 2007). IOA usually ranges from -1 to +1, with higher values indicating greater model performance.

## Results and discussion

The LSTM and Bi-LSTM models developed at the training station (Gazipur Sadar) were validated using meteorological data obtained from a test station (Barishal ststion) as well as recent data (for which the model was neither trained nor validated) obtained from the Gazipur station itself. The data of the test station were inputted to the developed LSTM model for predicting daily $ET_0$, which were then compared with the estimated $ET_0$ and different performance evaluation indices were computed using the model predicted and FAO-56 PM estimated $ET_0$ values. For multi-step ahead forecasting, new Bi-LSTM model was developed using the meteorological data from the Barishal station.

### *Generalization of the developed LSTM model for daily $ET_0$ prediction with the recent unseen test dataset: Gazipur station*

The performance evaluation results for the generalization capability of the developed LSTM model with the recent dataset for the Gazipur station is presented in Table 4. As evidenced by the computed performance evaluation indices, the performance of the LSTM model was as good as the training station performance (here training station indicates the same station with the differences in the data spanning). The LSTM model generalized the $ET_0$ values quite effectively when presented with the new unseen data. The model provided higher values of R and IOA as well as lower values of RMSE, MAE, and MAD indicating a reliable performance. The produced NS criterion was also acceptable with reference to the prediction modelling aspect. Model produced NRMSE value of less than 0.20 (0.171 in this effort) indicated a reasonably good performance of the proposed LSTM model for daily $ET_0$ prediction.

Table 4. Performance of the LSTM model for predicting daily $ET_0$ values

| Performance indices | Gazipur new dataset |
|---|---|
| | Entire dataset (from 01 July 2019 to 30 April 2022) |
| RMSE, mm $d^{-1}$ | 0.596 |
| NRMSE | 0.171 |
| R | 0.887 |
| MAD, mm $d^{-1}$ | 0.219 |
| MAE, mm $d^{-1}$ | 0.459 |
| NS | 0.719 |
| IOA | 0.933 |

The performance results are also presented in the forms of hydrographs and error plots (Figure 1). The $ET_0$ hydrograph revealed that there existed a very good matching between the FAO-56 PM estimated and LSTM predicted $ET_0$ values. The error plot also indicated the lower magnitude of errors in prediction at standalone data points.

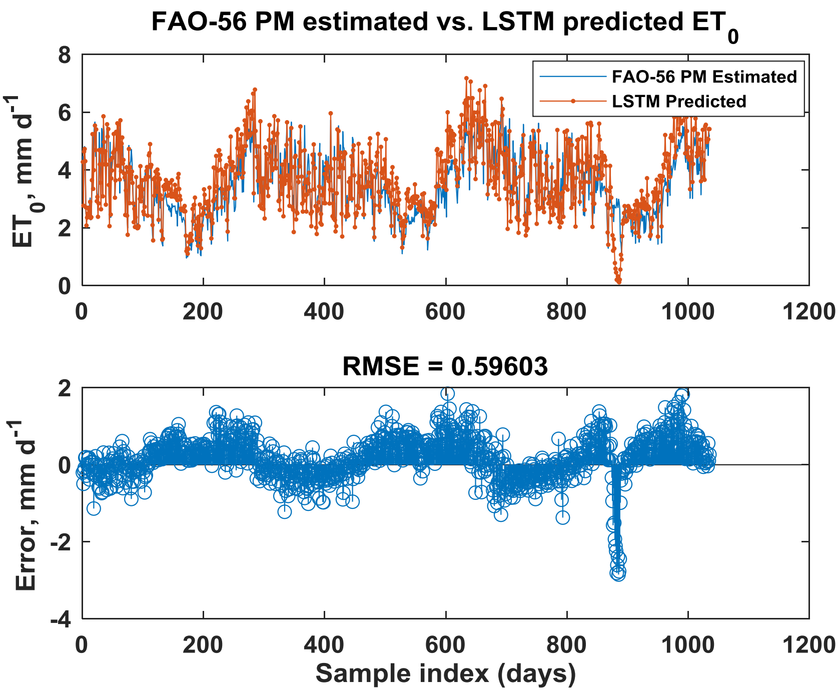


Figure 1. Time series and error plots of FAO-56 PM estimated and LSTM predicted daily $ET_0$ values at Gazipur station

***Generalization of the developed LSTM model for daily $ET_0$ prediction with the unseen dataset from a different station: Barishal station***

The performance evaluation results in terms of various statistical indices are shown in Table 5. As the results indicate, the models performed equally well when compared to the results of the training station. The model performances were satisfactory concerning the computed statistical indices: the model produced higher values of IOA, and R as well as lower values of RMSE, NRMSE, MAE, and MAD for the unseen datasets. Although NS criterion produced relatively lower values, the model prediction is deemed to be acceptable based on the other performance evaluation criteria. Overall, the performance is satisfactory, and based on that it can be concluded that the developed LSTM model at Gazipur station is able to predict daily $ET_0$ values at Barishal station without the need to develop model at Barishal station.

Table 5. Performance of the LSTM model for predicting daily $ET_0$ values at Barishal station

| Performance indices | Barishal dataset |
|---|---|
| | Entire dataset (from 01 January 2015 to 30 April 2022) |
| RMSE, mm $d^{-1}$ | 0.687 |
| NRMSE | 0.214 |
| R | 0.909 |
| MAD, mm $d^{-1}$ | 0.229 |
| MAE, mm $d^{-1}$ | 0.618 |
| NS | 0.559 |
| IOA | 0.904 |

Performance results are also presented in the form of scatter and error plots as shown in Figure 2, which indicate the distribution of errors at individual data points.

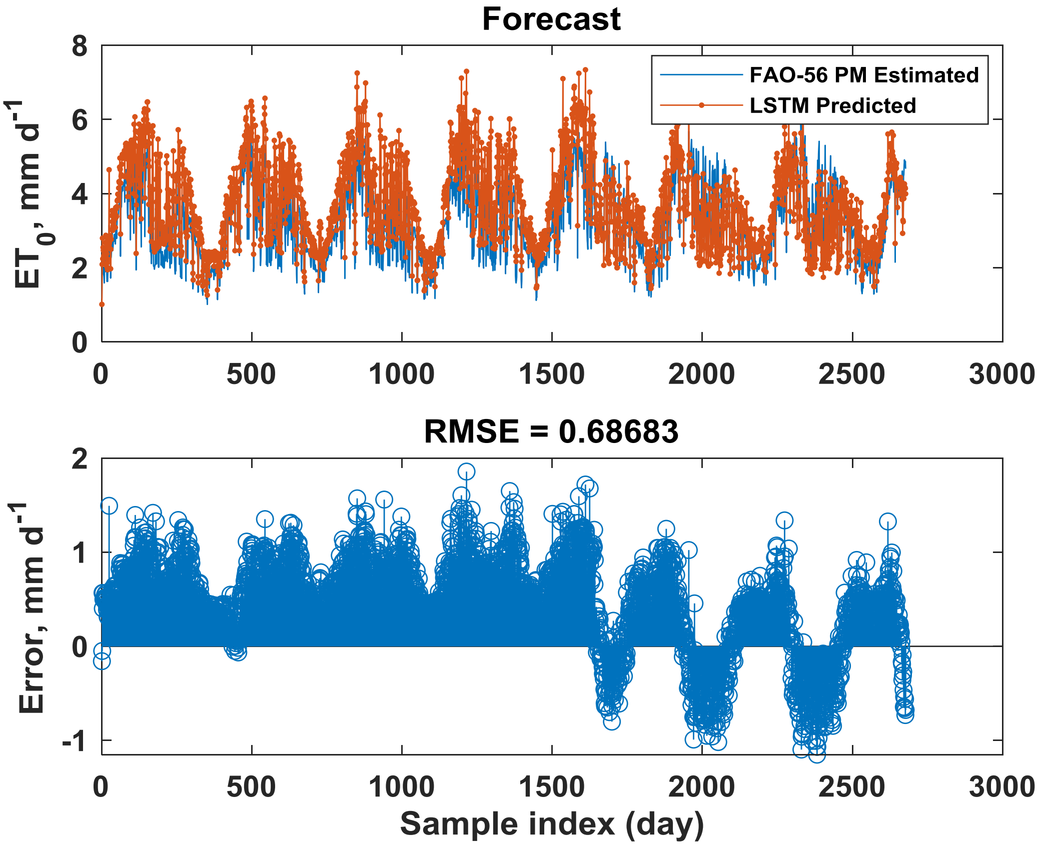


Figure 2. Scatter and error plots of FAO-56 PM estimated, and LSTM predicted daily $ET_0$ values at Barishal station (Entire dataset (from 01 January 2015 to 30 April 2022).

***Generalization of developed Bi-LSTM model for multi-step ahead forecasting with a new unseen test dataset: Barishal station***

For multi-step ahead forecasting, new Bi-LSTM models were developed because the nature of data as well as the number of input variables was different from the training station. However, the similar model structure and parameters as in the case of Gazipur station were used. As a Bi-LSTM model performed better for one-step ahead prediction at Gazipur station as well as five steps ahead forecasting at Ishurdi station, Bi-LSTM model was used to develop models for forecasting 1-, 2-, 3-, and 5-day ahead $ET_0$ values at the Barishal station. For this, time-lagged information from the $ET_0$ time series was collected for 50 lags. The most significant input variables were determined by observing partial autocorrelation functions of the lagged time series as shown in Figure 3. Fifteen input variables were selected based on the time lagged information obtained from the PACF plot illustrated in Figure 3. Therefore, inputs to the Bi-LSTM model was the 15 time lagged variables whereas outputs to the Bi-LSTM models were the one-day, two-days, three-days, four-days, and five-days ahead $ET_0$ values. Therefore, the inputs to the models (five models for five days ahead forecasts) were:

$$ET_0(d, d-1, d-2, d-3, d-4, d-5, d-6, d-7, d-8, d-9, d-10, d-11, d-13, d-15, d-48)$$

The outputs were:

$$ET_0(d+1, d+2, d+3, d+4, d+5)$$

After creating the time series of 50 lags, the total number of input-output training patters were amounted to 2622 from the original entries of 2677 $ET_0$ values. Eighty percent of the total dataset of

2622 entries was used for training (2098 entries) whereas the remaining 20% (524 entries) was used for testing of the developed model.

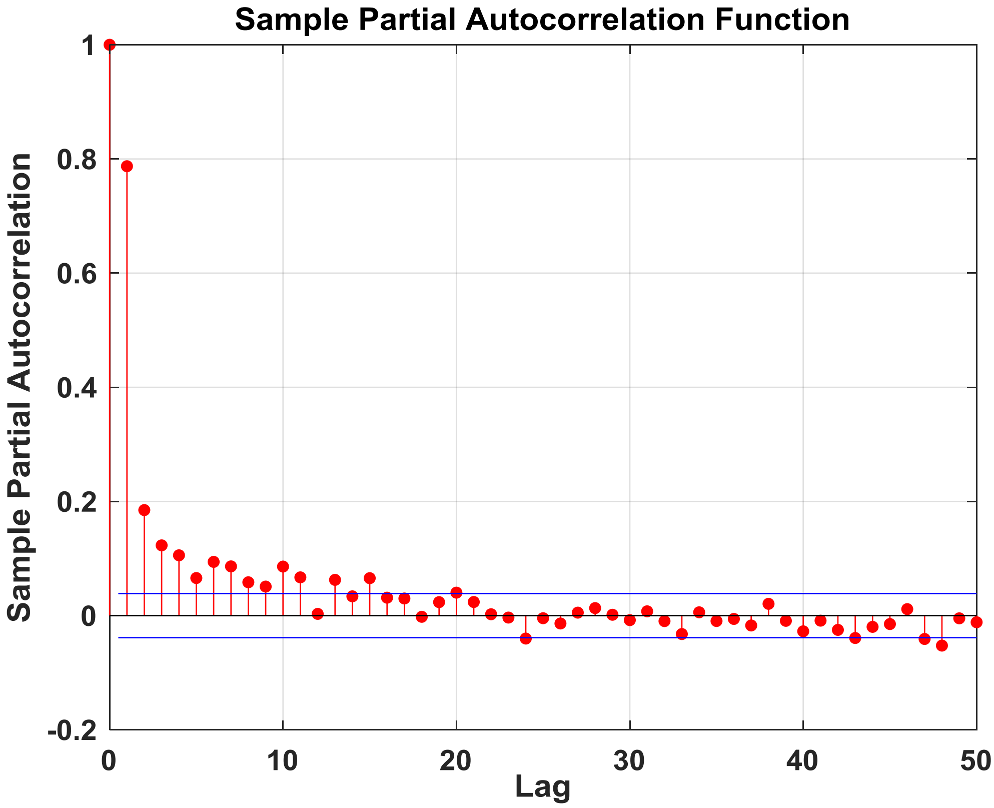


Figure 3. Sample partial autocorrelation functions of the lagged $ET_0$ time series.

Five Bi-LSTM models were developed to forecast 1-, 2-, 3-, 4-, and 5-day ahead $ET_0$ forecasting. For all models, the selected time lagged variables (15) were served as inputs to the Bi-LSTM models. Table 6 presents the training and validation performances as well as the training time requirements of the developed Bi-LSTM models. It is observed from Table 6 that the differences between the training and validation performances increased with the increase in the forecasting horizon. Overall, the training performances were satisfactory for all forecasting horizons. As far as the computational time requirements, the development of the models required almost the similar time ranging between 47 – 50 minutes (Table 6), which is rather low in any type of modelling studies.

Table 6. Training and validation performances of the developed Bi-LSTM models

| Forecasting horizon | Training RMSE, mm $d^{-1}$ | Validation RMSE, mm $d^{-1}$ | Training time, min |
|---|---|---|---|
| 1-day | 0.057 | 0.105 | 47.20 |
| 2-days | 0.060 | 0.144 | 46.88 |
| 3-days | 0.058 | 0.145 | 48.70 |
| 4-days | 0.084 | 0.230 | 48.21 |
| 5-days | 0.067 | 0.361 | 49.49 |

The trained and validated Bi-LSTM models were then used to forecast $ET_0$ values on the test dataset, which were selected from the entire dataset. Testing performances were evaluated using several statistical performance evaluation indices as presented in Table 7. It is observed from Table 7 that forecasting horizon greatly influenced the forecasting accuracies, and that the accuracy decreased with the increase in the forecasting horizon as in the case of the training and validation performances. However, the overall performances of the B-LSTM model for all forecasting horizons showed particularly good performance as indicated by the computed statistical performance evaluation indices. The R, NS and IOA criteria for the 1-day ahead forecasting were 0.996, 0.991, and 0.998, respectively whereas these values decrease to an almost negligible amount at 5-days ahead forecasting, the values of which were 0.943, 0.888, and 0.970, respectively for the R, NS, and IOA criteria. On the other hand, the RMSE, NRMSE, MAD, and MAE criteria also demonstrated a very little deviation between 1-day ahead to 5-days ahead forecasting (Table 7).

Table 7. Performance of the bi-LSTM model on the test dataset

| Indices | Forecasting horizon | | | | |
|---|---|---|---|---|---|
| | 1-day | 2-days | 3-days | 4-days | 5-days |
| RMSE, mm $d^{-1}$ | 0.104 | 0.144 | 0.145 | 0.230 | 0.361 |
| NRMSE | 0.033 | 0.045 | 0.045 | 0.071 | 0.112 |
| R | 0.996 | 0.992 | 0.992 | 0.982 | 0.943 |
| MAD, mm $d^{-1}$ | 0.022 | 0.029 | 0.028 | 0.064 | 0.107 |
| MAE, mm $d^{-1}$ | 0.064 | 0.077 | 0.080 | 0.169 | 0.244 |
| NS | 0.991 | 0.982 | 0.982 | 0.955 | 0.888 |
| IOA | 0.998 | 0.995 | 0.995 | 0.989 | 0.970 |

Performance of the developed models was also evaluated by means of line graph and error plots as shown in Figures 4, 5, 6, 7, and 8.

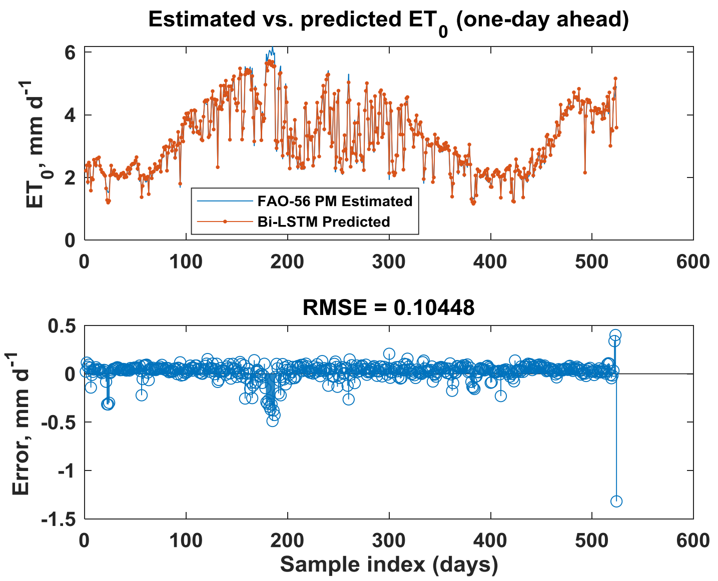


Figure 4. Line graph and error plots for 1-day ahead forecasting.

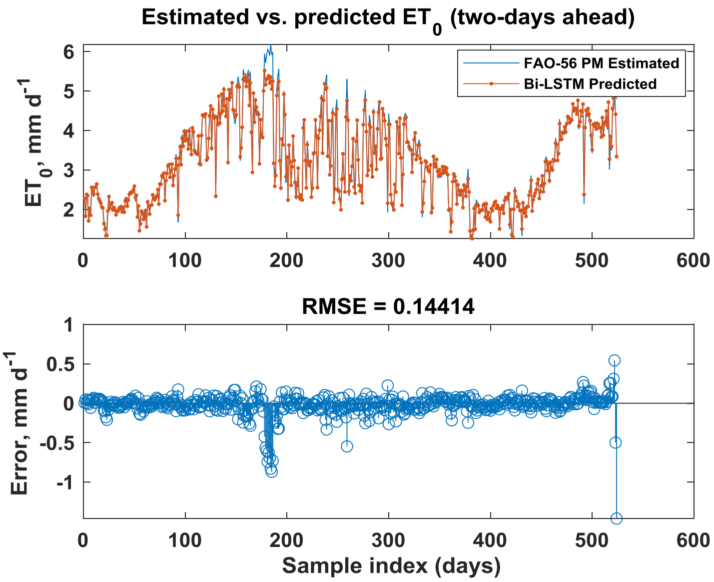


Figure 5. Line graph and error plots for 2-day ahead forecasting.

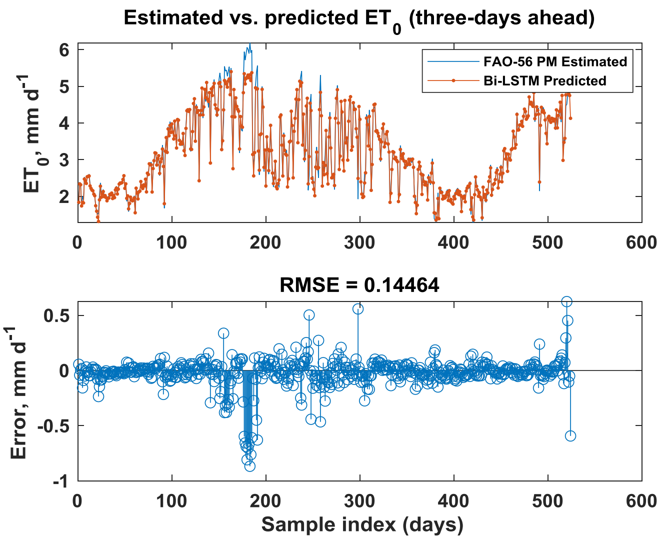


Figure 6. Line graph and error plots for 3-day ahead forecasting.

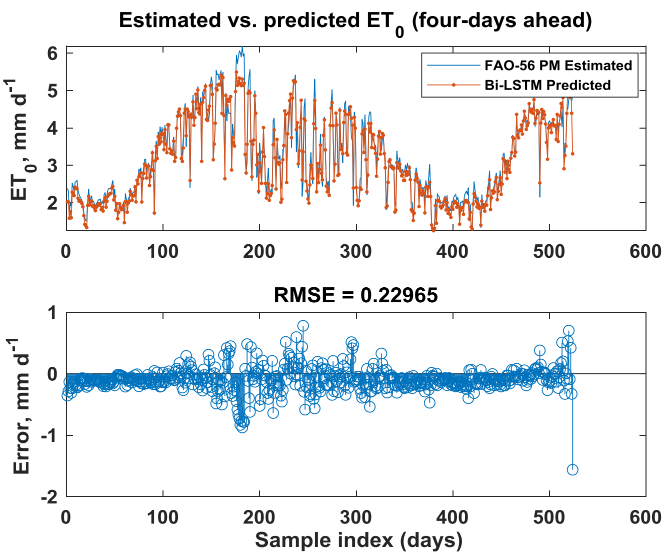

Figure 7. Line graph and error plots for 4-day ahead forecasting.

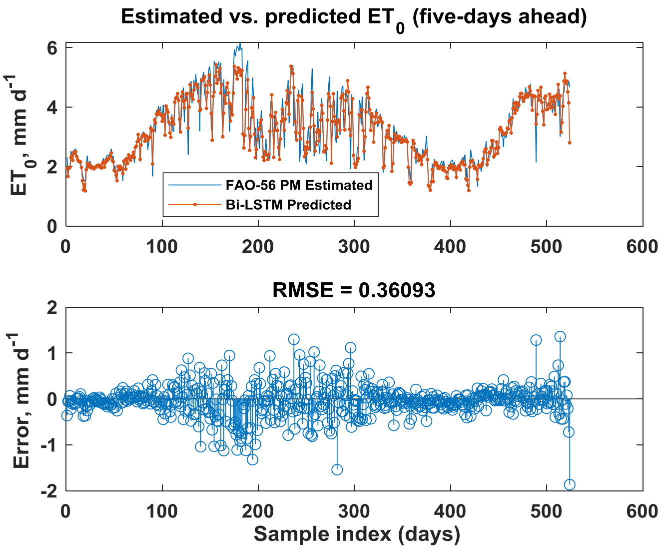


Figure 8. Line graph and error plots for 5-day ahead forecasting.

## Conclusions

Precise and reliable prediction of reference evapotranspiration can effectively be employed in developing a sustainable and efficient agricultural water management strategy. This study developed a robust prediction and forecasting tool for daily and multi-step ahead $ET_0$ values through deep learning algorithms: LSTM and bidirectional LSTM (Bi-LSTM) networks. LSTM network developed at Gazipur station was used to generalize the daily $ET_0$ predictions in a nearby meteorological station (Barishal) without developing model for that station. On the other hand, Bi-LSTM model was developed for the Barishal station to forecast 1-day, 2-days, 3-days, 4-days, and 5-days ahead $ET_0$ forecasting. Results revealed the suitability of the models in prediction daily $ET_0$ values and forecasting multi-step ahead (5-days ahead) $ET_0$ values. Both LSTM and Bi-LSTM models showed very good performance for both daily and multi-step (5-day ahead) predictions as indicated by the computed performance evaluation indices. The findings of this research demonstrated the ability of the developed deep learning model (LSTM) to generalize the prediction capabilities outside the training station. Multi-step ahead forecasting results revealed the practical applicability of the proposed Bi-LSTM model in forecasting days ahead $ET_0$ values.

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# GROWTH AND YIELD OF CHILLI AS INFLUENCED BY DIFFERENT LEVELS AND INTERVALS FOR DRIP IRRIGATION

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## Abstract

*Irrigation at the proper time and amount is important to get a good yield of shallow-rooted plants like chilli. A field experiment was conducted during the Rabi and start of the Kharif-1 (~6 months) season at the Irrigation and Water Management field in Gazipur to determine an efficient irrigation schedule of chilli (var. BARI Morich 1) using the drip irrigation method. There were two factors RCBD with irrigation intervals (every alternate day and 3 days) and irrigation amounts (100%, 75% and 50% of $ET_c$) with three replications. The result showed that 3 days irrigation interval gave ~37% higher chilli yield than that of every alternate day irrigation. It gave ~116% and 50% higher irrigation water productivity using 50% of crop $ET_c$ than that of 100% and 75% of crop $ET_c$. A 74% variation in chilli yield was recorded due to canopy cover at 158 days and 3 days irrigation interval also showed a higher canopy than that of every alternate day irrigation. This treatment also gave ~37%, 176% and 37% higher gross return, net return and benefit-cost ratio than that of every alternate day irrigation. Therefore, it is recommended to irrigate chilli at similar agro-climatic conditions at 3 days intervals with 50% of crop ET to get higher irrigation water productivity and net return.*

## Introduction

Chilli (Capsicum annuum L.) is a commonly consumed and cultivated spice crop worldwide (Olatunji, and Afolayan, 2018; Hunde, 2020). In Bangladesh, chilli is consumed by ordinary people as a must ingredient in their daily meals. Despite the fact the demand for chilli is increasing, the area under chilli production is gradually decreasing (Hasan, and Uddin, 2017). As the local production is incapable of meeting the demand, we often import a large amount of chilli each year. Therefore, there is a huge scope for increasing the local production by introducing high-yielding varieties and improving cultural management practices. As chilli is a water-sensitive crop, its production can be influenced largely by the change in soil moisture status (Kopta et al., 2020). Generally, furrow irrigation is used as common practice for chilli production in Bangladesh, which has less control over maintaining root-zone soil moisture levels. Whereas a more controlled irrigation method like drip can provide an opportunity to maintain desired/ optimum moisture level according to the need of the plants. Therefore, a comprehensive study is needed to study the effect of drip irrigation with varying amounts of water and different application intervals. There are the following objective:

(i) To determine an efficient and economic irrigation schedule for chilli with the use of drip and supplemental drip irrigation at different amounts and timing.

## Materials and Methods

The experiment was conducted at the research farm of the Irrigation and Water Management Division at Bangladesh Agricultural Research Institute, Joydebpur, Gazipur. The weather variables of maximum and

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minimum temperature during the day and night varied from 21.0-36.7°C and 10-28.6°C. The cumulative evaporation during the season remained ~642 mm. The cumulative rainfall during the season remained at 1328 mm.

The crop (variety: BARI *Morich* 1) was transplanted on 6 January 2022 at the age of 30 days on a 1.2 m x 3.6 m bed. Each bed carried two rows of plants with a spacing of 60 cm and plant-to-plant spacing of 60 cm. After transplanting, a light watering (~1-3 L/plant) with manual weeding was done as necessary. Recommended fertilizer was applied based on the BARI recommended fertilizer (Krishi Projukti Hatboi 2020). The Irrigation was started using the drip irrigation method and applied based on crop growth stages. The crop growth stages were divided into four developmental stages namely, initial, developmental, mid-season, and late-season stage for the aid of irrigation application. Irrigation amount was applied based on crop evapotranspiration ($ET_c$). The crop evapotranspiration was calculated by multiplying reference ET ($ET_o$) and crop coefficient ($K_c$) values and these values were taken from Islam et al., 2020.

The experimental design was 2-factors RCBD; Factor A—two irrigation intervals (every alternate day and 3 days interval) and Factor B—three irrigation amounts (100, 75 and 50% of $ET_c$) with 3 replications. The crop was harvested six times (from 91-175 days after transplanting). After harvest, the number and weight of green and red chilli were recorded. Plant growth data of plant height, branch number and canopy coverage were recorded during mid to late seasons. The proportion of green leaves at crop growth stages was measured using a grid suggested by Burstall and Harris (1983). A wooden frame with 100 equal sections of dimension 0.50 m × 0.50 m was used based on crop spacing and the detailed procedure of placing and counting the grid was given in Mila et al. 2017. Therefore, canopy cover (expressed as a percentage) was calculated by the ratio of the area of grids covered by green leaves to the total area of the grid for the crop (Mila et al. 2017). Here we calculated for the single crop. Soil moisture was collected at 0-15 and 15-30 cm soil depth during sowing and harvest. Six drip irrigation sets with 200 L tanks were installed at the height of 1 m and each of the tanks covered three reps. The dripper discharge was 3.5 L/hr/plant. The plant was irrigated based on the time passed to meet the required amount of water. The volume of water (L/day) was calculated by multiplying $K_C$, $ET_o$ and the area occupied by a single plant. Crop water use, water productivity and irrigation water productivity were calculated based on the formula used in Mila 2022.

To test the economic feasibility of the drip irrigation system using different irrigation intervals and amounts, the total cost for 1000 $m^2$ of land was calculated by the summation of total operation cost, interest on operation cost (5% per season), drip irrigation installation cost and land use cost. The total operating cost involved the cost related to land preparation, chilli seedling, fertilizer, pesticide, irrigation, and labour. The expected life of the drip irrigation system was considered for 8-10 years. In the following years, depreciation, and repair and maintenance cost will be added instead of setting the cost of the drip irrigation system.

Analysis of variance for yield and yield attributes was done using R and Jamovi software. Regression analysis between yield and yield attributes or plant growth parameters was done by Jamovi and Excell software.

## Results

### Table 1

Estimated crop water requirement for irrigation interval and amount at crop growth stages of chilli

| Crop stage | Duration (day) | $K_c$ | $ET_0$ (mm/day) | $ET_c$ (mm/day) | Area occupied ($m^2$/plant) | $ET_c$ (L/day) | Dripper discharge (L/hr) |
|---|---|---|---|---|---|---|---|
| Initial | 16 | 0.42 | 3.3 | 1.4 | 0.36 | 0.5 | 3.5 |
| Development | 20 | 0.78 | 4.6 | 3.6 | 0.36 | 1.3 | 3.5 |
| Mid-season | 109 | 1.27 | 1.3 | 1.7 | 0.36 | 0.6 | 3.5 |
| Late season | 21 | 0.86 | 4.3 | 3.7 | 0.36 | 1.3 | 3.5 |

†$K_c$, $ET_o$ and $ET_c$ denote crop coefficient, reference evapotranspiration and crop evapotranspiration.

### Number and weight of green and red chilli per plant over time

Fig.1 shows the pattern of changes in the number and weight of green and red chilli per plant over time for 6 harvests. Overall, the number and weight of green chilli were highest (~43% of total) during the reproductive stage (at the 4th harvest on day 154) (Fig. 1a, c), while the red chilli showed two peaks during reproductive (~33% of the total at 3rd harvest on day 125) and fruit ripening stage (~46% of the total at 6th harvest on day 175) (Fig. 1b, d). Compare with irrigation intervals, 3 days irrigation intervals gave ~65% higher number and weight of green chilli during the 4th harvest (Fig. 1a, c). Similarly, for red chilli, 3 days irrigation intervals gave 69% and 94% higher number and weight of red chilli during the 3rd harvest (Fig. 1b, d). Compare with irrigation amounts, 50% of $ET_c$ gave ~24% and ~31% significant higher number and weight of green chilli during the 4th harvest (Fig. 1e, g). However, in terms of interactions, although not significant showed that 3 days of irrigation with three irrigation amounts were dominated.

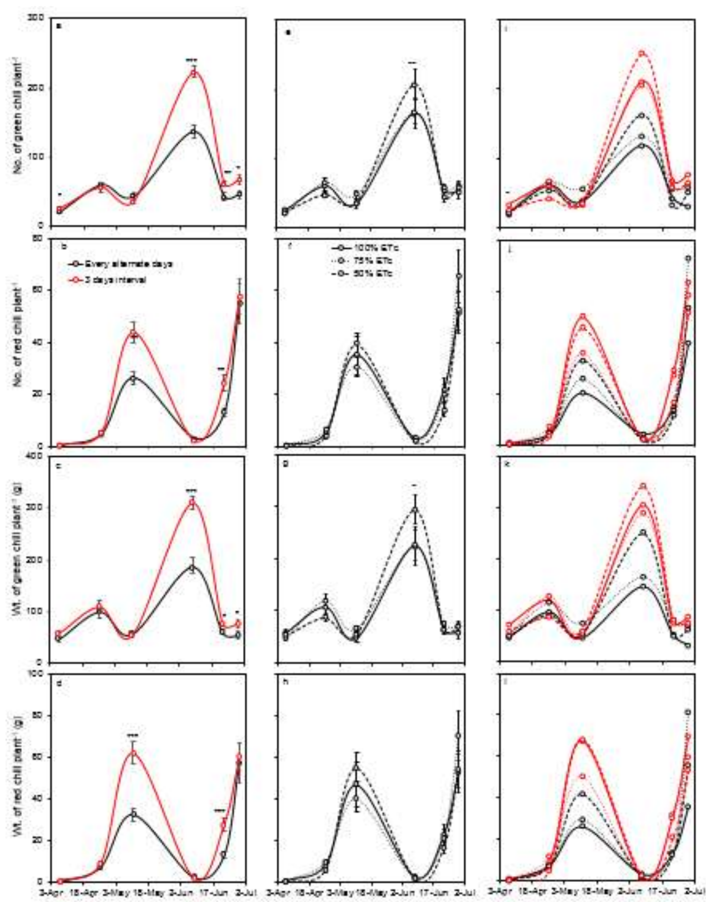


**Fig.1** Changes in number and weight of green and red chilli plant$^{-1}$ for the effect of irrigation intervals (a-d), irrigation amounts (e-h) and combination of both (i-l) for the timing of six harvests. Black and red colour indicate irrigation interval for every alternate day and 3 days. The solid, round dot and square dot lines indicate 100%, 75% and 50% of ETc. The bar represents the mean ±SE. The significance level of *, ** and *** denote the probability of < 0.05, < 0.01 and < 0.001.

**Table 2**

ANOVA for the yield and yield components, seasonal water use (SWU), water productivity (WP) and irrigation water productivity (IWP) of chilli

| Name of the treatments | Chilli yield (t/ha) | Wt. of chilli plant$^{-1}$ (g) | | | No. of chilli plant$^{-1}$ | | | Irrigation (mm) | SWU (mm) | WP (kg m$^{-3}$) | IWP (kg m$^{-3}$) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Green | Red | Total | Green | Red | Total | | | | |
| Irrigation intervals (I) | <0.001 | <0.001 | <0.05 | <0.001 | <0.001 | <0.05 | <0.001 | ns | <0.05 | <0.001 | <0.001 |
| Irrigation amounts (A) | ns | ns | ns | ns | ns | ns | ns | <0.001 | <0.001 | <0.01 | <0.001 |
| I*A | <0.05 | ns | ns | <0.05 | ns | ns | <0.05 | ns | ns | ns | ns |

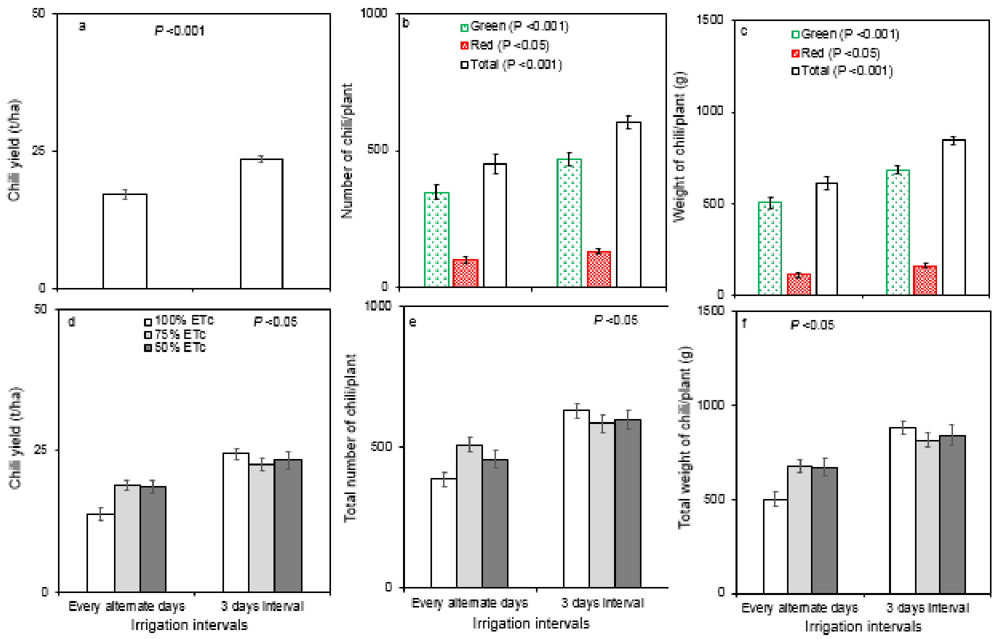


**Fig.2** Chilli yield (a, d) and yield attributes (b, c, e, f) for the individual effect of irrigation intervals and combined effect of irrigation intervals and amounts. (a) chilli yield for the individual effect of irrigation intervals, (b, c) number and weight of green, red or total chilli plant$^{-1}$ for the individual effect of irrigation intervals, and (d-f) chilli yield, total weight and number of chilli plant$^{-1}$ for the interaction effect of irrigation intervals and irrigation amounts. The bar represents the mean ±SE.

**Effect of irrigation intervals and irrigation amounts on chilli yield and yield attributes**

The effect of irrigation intervals and irrigation amounts on chilli yield and yield attributes are shown in Table 2. Analysis of variance showed that chilli yield and yield attributes for the effect of irrigation intervals were significant ($P$ <0.001 and $P$ <0.05). Among them chilli yield, weight and number of green and total chilli were highly significant ($P$ <0.001). On the other hand, ANOVA for interaction effects was mostly insignificant while chilli yield, total weight and number of chilli plant$^{-1}$ were poorly significant ($P$ <0.05).

The bar diagram shows the significant highest chilli yield was recorded for the plant irrigated at 3 days interval, which was ~37% higher than that of every alternate day irrigation (Fig. 2a). Similar result was recorded for the number and weight of green, red and total chillies (Fig. 2b and 2c). Irrespective of irrigation intervals, the number and weight of green chilli accounted for ~78% and ~81% of the total number and weight of chilli (Fig. 2b, c).

**Effect of irrigation intervals and irrigation amounts on irrigation and crop water use**

ANOVA table shows that irrigation and seasonal water use were highly significant for the effect of irrigation amounts (Table 2). Overall, irrigation amount increased with the increased use of irrigation water which is associated with increased seasonal water use. Irrigation with 100% of $ET_c$ recorded the significant highest irrigation water use of ~200 mm. This treatment used ~32% and 48% higher irrigation water than that of 75% and 50% of crop ET (Fig.3b). Similar trend was found for seasonal water use. The highest water used treatment (100% of crop ET) gave ~8% higher water use than that of 75% and 50% of crop ET (Fig.3d).

**Effect of irrigation intervals and irrigation amounts on water productivity and irrigation water productivity**

ANOVA table shows that water productivity and irrigation water productivity were significant for the effects of irrigation intervals and irrigation amounts (Table 2). Overall, irrigation at 3 days interval gave ~26% and ~20% higher water productivity and irrigation water productivity than that of every alternate day irrigation (Fig. 3e, g). Overall, lower water used treatment gave the highest water productivity than that of higher water used treatment (Fig. 3f, h). For example, 50% of crop $ET_c$ gave ~116% and 50% higher irrigation water productivity than that of 100% and 75% of crop $ET_c$ (Fig.3h). Similar trend was found for water productivity although they are not significant (Fig. 3f).

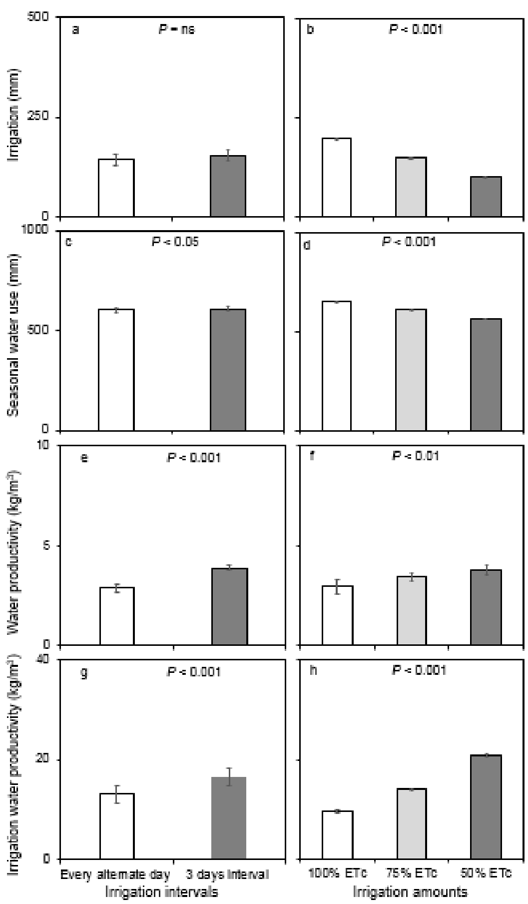


**Fig.3** Crop water-related terminology of irrigation (a, b), seasonal water use (c, d), water productivity (e, f) and irrigation water productivity (g, h) of chilli for the effect of irrigation intervals and irrigation amounts. Here, $ET_c$ denotes crop evapotranspiration. The bar represents the mean ±SE.

**Effect of irrigation intervals and irrigation amounts on plant growth and yield**

The correlation matrix of chilli yield and plant growth parameters of plant height, canopy cover, primary and secondary branch showed that chilli yield was highly significant with canopy cover in the late season. The regression relationship between chilli yield and canopy cover at 158 days after transplanting showed a significant positive relationship ($P$ <0.001 and $r^2$ = 0.74) (equation 3).

Chili yield = – 4.02 + 0.31 x canopy cover $plant^{-1}$ at 158 days after transplanting (Equation 3)

**Economic analysis of irrigation intervals and irrigation amounts of Chili**

Overall, three days irrigation interval gave ~37, 176 and 37% higher gross return, net return and benefit-cost ratio than that of every alternate day irrigation (Table 3). However, the variation in total cost was negligible due to the variation in irrigation amount and intervals.

**Table 3**

Total cost, gross return and net return of BARI *Morich* 1 for different irrigation intervals and amounts for 1000 $m^2$ of land in the 2022 crop season

| Name of the treatment | Total cost | Gross return | Net return | Benefit-cost ration |
|---|---|---|---|---|
| Every alternate day at 100% ETc | 331015 | 339882 | 8867 | 1.0 |
| Every alternate day at 75% ETc | 330837 | 462569 | 131731 | 1.4 |
| Every alternate day at 50% ETc | 330659 | 456119 | 125460 | 1.4 |
| Three days interval at 100% ETc | 331060 | 598537 | 267476 | **1.8** |
| Three days interval at 75% ETc | 330871 | 555297 | 224426 | **1.7** |
| Three days interval at 50% ETc | 330682 | 573097 | 242415 | **1.7** |

## Conclusion

Chilli is a shallow-rooted plant and sensitive to drought and flood and needs to maintain homogeneous soil moisture within the root zone to get a higher yield, irrigation water/ water productivity and net margin. The year 1 study with irrigation interval and irrigation amounts showed that ~37% higher chilli yield was recorded by irrigating 3 days intervals than that of every alternate day. Similar results were found for yield components of number and weight of green, red and total chillies. 3 days irrigation interval gave ~116% and 50% higher irrigation water productivity using 50% of crop $ET_c$ than that of 100% and 75% of crop $ET_c$. Plant growth parameters of canopy cover at 158 days showed a significant positive relationship with a yield at $r^2$ values of 0.74. Similarly, 3 days irrigation interval gave ~37%, 176% and 37% higher gross return, net return and benefit-cost ratio than that of every alternate day irrigation. Therefore, it can be concluded that the chilli plant can be irrigated at 3 days intervals at 50% of $ET_c$ and can get higher irrigation water productivity and economic benefit.

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# OPTIMUM WATER AND FERTILIZER MANAGEMENT OF DWARF SUNFLOWER USING APSIM (FIELD EXPERIMENT)

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## Abstract

Proper use of irrigation and fertilizer at proper crop growth stages can minimise misuse of these costly inputs and can increase water use efficiency. Therefore, this field study was conducted in 2022 using dwarf sunflower (BARI *Surjamukhi* 3) at Irrigation and Water Management Division at Bangladesh Agricultural Research Institute, Gazipur located at AEZ no. 28 to get the best combination of full and 70% of full irrigation and urea at crop growth stages for increasing water productivity or irrigation water productivity. There were six irrigation combinations with full and 70% of full irrigation and full urea applied at 4 (vegetative, pre-flowering, flowering and grain filling), and 3 crop growth stages with or without grain filling. We found that three irrigation at vegetative, pre-flowering, flowering/grain filling with a full dose of urea is sufficient to get a good yield of dwarf sunflower. We also found that higher irrigation water productivity and water productivity are possible by lowering the amount of irrigation application by skipping irrigation at grain filling stages. Therefore, from the year 1 trial, it can be concluded that dwarf sunflower can be irrigated both full and 70% of full irrigation and full urea at vegetative, pre-flowering and flowering stages to increase water productivity or irrigation water productivity by decreasing crop water use and irrigation in central Bangladesh.

## Introduction

Options for improved resource use efficiency for agricultural crop production can be assessed by using crop simulation models. Provided they are well-calibrated and validated, crop simulation models can obviate the need for large numbers of field experiments and can examine the long-term impacts of new technologies, varieties and cropping systems. Both water and fertilizer are important inputs for the growth and development of most crops and efficient use of these resources can increase system efficiency and profitability. In an agricultural production system, crop productivity is influenced by the weather parameters, soil type, soil water, soil nutrient, depth of water table, crop phenology and physiology. The Agricultural Production Systems Simulator model (APSIM) is a platform for simulating biophysical processes of crops in cropping systems. When well-calibrated, this model provides an accurate estimation of crop production in relation to climate, genotype, soil and farmer management factors while addressing the long-term natural resource management issues and climate change scenarios. Sunflower is a promising new crop in Bangladesh, but there is still limited field evaluation of its yield potential. Crop modelling of sunflower could be an efficient way of understanding its yield potential and adaptation to different AEZ and cropping seasons in Bangladesh. However, first, a well-calibrated model needs to be developed and validated. To do this we need to grow sunflower in the field with the use of either full or deficit irrigation and urea at different crop growth stages varying from three to four. Although, BARI recommended irrigation and urea schedule for sunflower at crop growth stages of vegetative, flowering and grain filling (BARI Agricultural technology handbook 2020). However, in this recommendation, they emphasised the increased yield without considering the valuable resources of water and urea. We hypothesised that

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full and 70% of full irrigation and full urea at vegetative, pre-flowering and flowering stages can increase water productivity or irrigation water productivity by decreasing crop water use or irrigation of dwarf sunflower. In this study, we will use a new dwarf sunflower variety to test the APSIM sunflower module.

In this case, water productivity, irrigation water productivity and also fertilizer productivity can be important variables to get the answer to the question: which stage of irrigation and urea with either recommended or 70% of the recommended amount is important to get a good yield and higher water and (or urea productivity) of sunflower? This study has the following objectives:

1. To conduct field experiment for more than two seasons
2. To parameterize and calibrate the model
3. To validate the model by representing field data and
4. Finally to simulate the model

## Materials and Methods

The experiment was conducted at the experimental field of Irrigation and Water Management, Bangladesh Agricultural Research Institute, Joydebpur, Gazipur, Bangladesh (Latitude 24°00 ′N, longitude 90°25 ′E, and elevation 8.4 m from mean sea level, Mila et al., 2016). The weather parameters of maximum and minimum temperature during the day and night varied from 27-36.7°C and 10-21°C. Cumulative rainfall during the crop season was ~62 mm among them vegetative (day 23-day 24) and grain filling (day 74-day 78) stages received ~ 36 mm and 26 mm of rainfall. Cumulative evaporation during the crop season was ~331 mm among them mean daily evaporation during January, February, March, and April were ~ 2.1, 2.9, 4.9 and 4.5 mm, respectively. The soil texture within 0-1.2 m varied from sandy loam to loam with bulk density and field capacity varied from 1.47-1.62 g $cc^{-3}$ and 25.8-33.3%, respectively. The chemical properties of soil $p^H$ and organic matter varied from 5.5-7.3 and 0.55-1.55 %. Other parameters were within the tolerable limit.

The dwarf sunflower variety of BARI *Surjamukhi* 3 was sown in line on 13 January 2022. The unit plot size was 2.5 m X 3.9 m and the plant spacing was 50 cm X 30 cm. The buffer was kept 1.6 m X 2.1 m. Three seeds were sown at each point. After establishment, thining was done twice by uprooting one plant on day 13 and another one on day 25. Insecticide Nitro 505 EC was applied @ 1 ml $litre^{-1}$ of water three times (day 35, 42, 49). Irrigation and fertilization were applied according to the design of the treatments. The experimental design was RCBD with three replications. There were six irrigation and urea treatments. Among them, three were full irrigation and urea at four crop growth stages (vegetative, pre-flowering, flowering and grain filling), three crop growth stages with or without grain filling, and another were 70% of full irrigation and urea at the same crop growth stages.

Before sowing, two sets of urea (half of 100% and 70% of BARI recommended) with 100% of other fertilizers were applied. The rest half of 100% and 70% of urea was divided into two equal splits; one applied on day 26 (7 February 2022 or V4 stage) and another was applied on day 41 (22 February 2022 or pre-flowering stage). The BARI recommended 100% fertilizer dose is: Urea @ 200 kg $ha^{-1}$, TSP @ 180 kg $ha^{-1}$, MoP @ 170 kg $ha^{-1}$, gypsum @ 170 kg $ha^{-1}$, $ZnSO_4$ @ 10 kg $ha^{-1}$, $H_3BO_3$ @ 12 kg $ha^{-1}$, $MgSO_4$ @ 100 kg $ha^{-1}$ and cowdung @ 8000 kg $ha^{-1}$ (BARI Agricultural technology handbook 2020). At the vegetative stage, no irrigation was applied because of heavy rainfall (~36 mm) on days 23-24. Basin irrigation method was used to irrigate the plant. Irrigation was applied based on soil moisture deficit up to 100% and 70% of field capacity at crop growth stages and the formula for calculating irrigation depth and volume was done by following Mila 2021. For this soil field capacity soil moisture was ~31%, root zone depth of 40, 50 and 60 cm for pre-flowering, flowering and grain filling stage and mean BD was ~1.56 g $cm^{-3}$ respectively. The sunflower crop was harvested on 13 April 2022 (day 91). During harvest 10 plants were collected to record yield and yield attributes of number of mature seed $plant^{-1}$, weight of mature seed $plant^{-1}$, weight of disk, diameter of disk, number of curl seed $plant^{-1}$, weight of curl seed $plant^{-1}$, % immature seed and 1000-seed weight.

Soil moisture was collected from five depths (0-15, 15-30, 30-50, 50-80 and 80-120 cm) eight times (day 1, 22, 25, 34, 47, 53, 67 and 91) by using hand-held auger.

ANOVA for yield, yield attributes, irrigation, water use, water productivity, and irrigation water productivity was done using R software (Team, R.C., 2013).

## Results

*Irrigation amount at different crop growth stages for full and 70% of full irrigation and urea (FI+FU and 70% of FI+FU) treatments*

A bar diagram showing the amount of irrigation used with lettering at different crop growth stages for the combination of full and 70% of full irrigation and urea (FI+FU and 70% of FI+FU) treatments (Fig 1a). An increase in the frequency of irrigation increases water amount, and this amount varied with or without irrigation at the end of crop growth stages. We found FI + FU at 4 crop growth stages needed a total of 344 mm irrigation. On the other hand, 70% of FI + FI at 4 crop growth stages needed a total of 241 mm where crop growth stages received a 30% lower amount than that of FI + urea for 4 crop growth stages. The water requirement for FI + FU at 3 crop growth stages including GF was ~77% higher than that of FI + FU at 3 growth stages excluding the GF stage, where the GF stage receive ~3 times of F stage irrigation.

*Crop water use at different full and 70% of full irrigation and urea (FI+FU and 70% of FI+FU) treatments*

Crop water use (CWU) (Fig. 1b) also followed the same pattern as irrigation amount for the full and 70% of full irrigation and urea (FI+FU and 70% of FI+FU) treatments. Here, the irrigation amount was 62 mm and SWC varied from 83-104 mm. The CWU for FI+FU and 70% of FI+FU for 4 crop growth stages were 500 and 403 mm. On the other hand, CWU for FI+FU and 70% of FI+FU for 3 crop growth stages excluding GF was 295 and 260 mm while including GF was 385 and 334 mm, respectively.

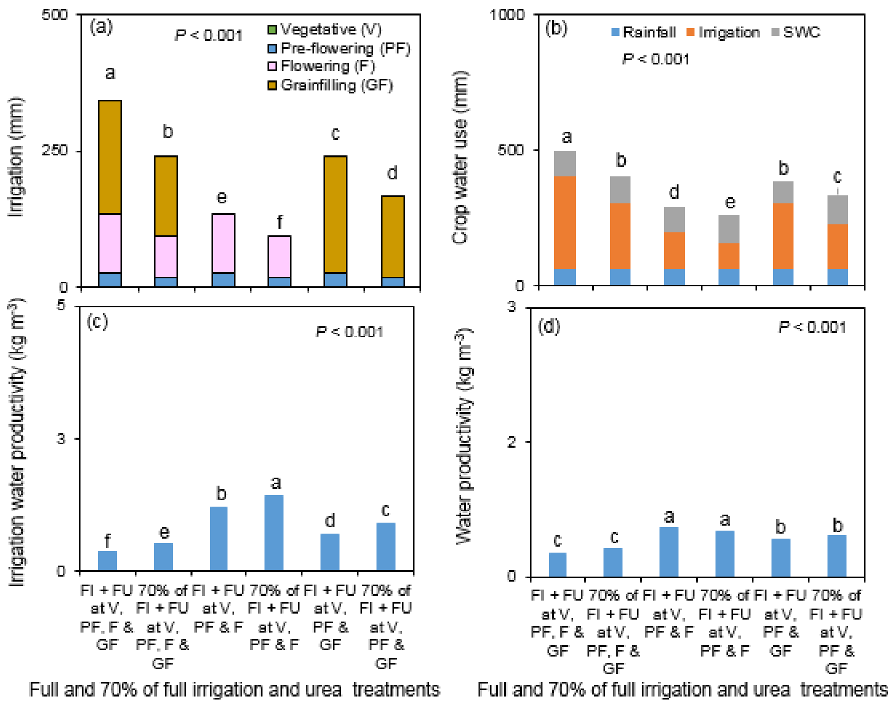


**Fig. 1** Irrigation (a), crop water use (b), irrigation water productivity (c) and water productivity (d) against different full and 70% of full irrigation and urea treatments. FI and FU denote full irrigation and full urea.

*Soil water status for different full and 70% of full irrigation and urea (FI+FU and 70% of FI+FU) treatments*

Overall, soil water decreases during the crop season with the progress of time while two peaks were recorded one on day 25 (due to rainfall) and another on day 55 (due to irrigation at the flowering stage) (Fig. 2). However, at the end of the season, some variation in soil water was recorded at the 0-15 cm soil depth.

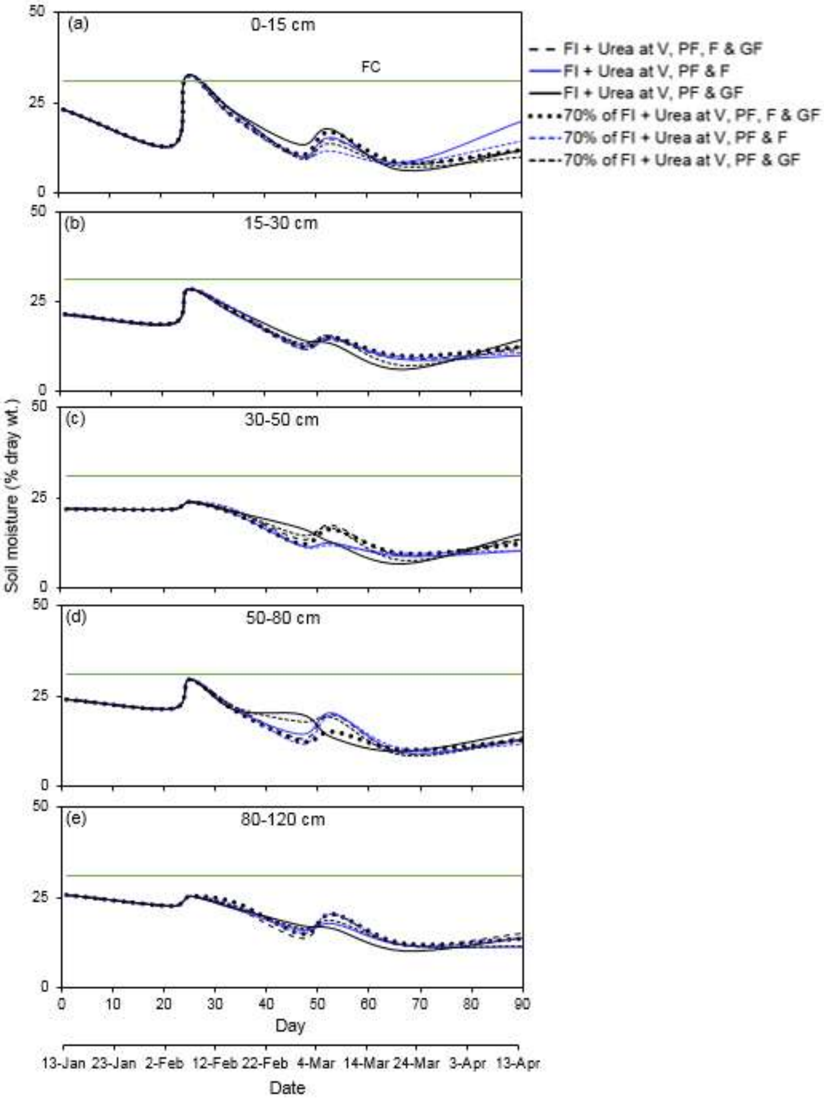


**Fig. 2** Soil moisture status at (a) 0-15, (b) 15-30, (c) 30-50, (d) 50-80 and (e) 80-120 cm soil layer during the study period in 2022.

*Yield and yield attributes at different full and 70% of full irrigation and urea (FI+FU and 70% of FI+FU) treatments*

ANOVA for yield and yield attributes showed that seed yield and weight of mature seed per plant are significant ($P < 0.01$). The bar diagram in Fig. 3 shows seed yield for various combinations of full and 70% of full irrigation and urea (FI+FU and 70% of FI+FU) treatments. The significant highest yield (~1.65 t ha$^{-1}$) was recorded for FI + FU at three crop growth stages with or without grain filling (GF) stage, while no significant difference was recorded for 70% of FI+FU at three crop growth stages including GF. 70% of FI+FU for three-crop growth without GF gave 1.35 t ha$^{-1}$ yield, which was insignificant with 70% of FI+FU for three crop growth without GF. On the other hand, the four irrigation treatments with full and 70% of full gave the significant lowest yield.

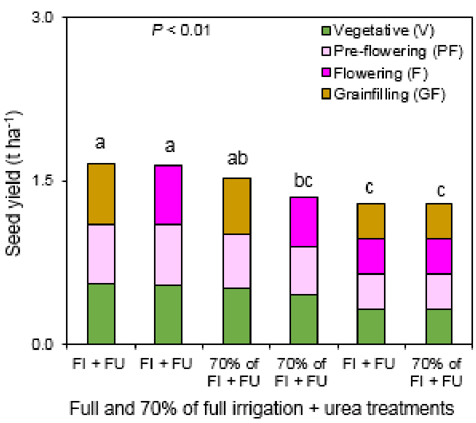


**Fig. 3** Seed yield against different full and 70% of full irrigation and urea treatments used in the 2022 crop season.

*Irrigation water productivity (IWP) and water productivity (WP) at different full and 70% of full irrigation and urea (FI+FU and 70% of FI+FU) treatments*

Fig. 1(c) is showing a bar diagram for highly significant IWP for different FI+FU and 70% of FI+FU treatments. Overall, IWP increases with the minimum use of irrigation water. The significant highest IWP was recorded for three FI and 70% of FI + FU treatments. The significant lowest IWP was recorded for four FI and 70% of FI + FU treatments. A similar trend was observed for the bar diagram showing highly significant WP for different FI+FU and 70% of FI+FU treatments (Fig. 1d).

## Conclusion

Irrigation and fertilizer both are important input for getting a good yield of dwarf sunflower and proper timing and amount of application can increase water use or irrigation use efficiency. In this year 1 trial, we found that three irrigation at vegetative, pre-flowering, flowering/grain filling with full dose of urea is sufficient to get a good yield of dwarf sunflower. We also found that higher irrigation water productivity and water productivity is possible by lowering the amount of irrigation application by skipping irrigation at grain filling stages. This study can be repeated for next year due to the rainfall variability and conformation of the year 1 results and also for Model input.


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# EFFECT OF IRRIGATION AND MULCHING ON GROWTH AND FLOWERING OF CHRYSANTHEMUM AS CUT FLOWER

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## Abstract

The experiment was conducted in the experimental field of IWM Division, BARI, Gazipur during 2020 -21 and 2021-22 to evaluate the effect of different irrigation amount with different mulching systems on growth and flowering of chrysanthemum as cut flower. The treatments comprised different combinations of three drip irrigation levels (100, 80 and 60% of $ET_0$) and three mulching systems (no mulch, black plastic and straw mulch) followed by RCBD design with three replications. Black plastic mulch conserves the highest moisture status and temperature among the three mulching system with each irrigation level and the lowest was from no mulch system. The lowest soil moisture enhances early flowering by one to two days but did not affect the burst bud diameter. Plant height was the highest with the lowest deficit moisture condition. When decreasing irrigation amount from 100 to 80%, plant leaves was increased in chrysanthemum during 2020-21, but at 2021-22 it was observed from 100% irrigation level. Stem length, number of branches/plant, number of bud/plant, number of flower/ branches, number of flowers/plant in chrysanthemum were increased when moisture content was also increased, but flower diameter was reduced with the constant highest moisture condition. The highest marketable branch/ plant, flowers/marketable branch, marketable branch/10m$^2$ were obtained from moderate moisturized soil. High water stress enhanced the plant fresh weight and dry weight destructively, decreased it to the lowest level. Constant higher moisture content conditions in the range of 24.69% to 31.18% showed decreasing fresh and dry weight patterns of chrysanthemum. The highest plant quality was generally produced under the paddy straw mulch with 100% $ET_0$ of irrigation level. A decrease in water stress reduced the root length of chrysanthemum, but increased the root fresh weight and dry weight. Consequently, plant root to shoot ration increased with the increasing level of water stress. The water productivity was generally decreased by 30±84% in consecutives two years might be due to reduced yield. The highest BCR was found for paddy straw mulch with optimum irrigation level followed by black plastic mulch and paddy straw mulch with 20% less irrigation water. However, results of this study revealed that the drip system of irrigation at 100% $ET_0$ or 80% $ET_0$ with black plastic mulch or paddy straw mulch or no mulch system with 100% $ET_0$ of water could be adopted by the farmers based on their feasibility and water availability for gladiolus cultivation in Bangladesh.


## Introduction

Floriculture has been identified as an emerging sector of agriculture in Bangladesh due to divergence of farmers towards high value floriculture and utilization of flowers in social occasion. Chrysanthemum is one of the most important flower crop of commercial importance grown in different parts of the world as cut flower and potted plant. In International flower trade, it ranks next to rose. Preferred particularly for its range of shapes and size of flower, brilliant color tones and long lasting flower life. As in all plants, irrigation is an essential practice for chrysanthemum growing, but its adequate handling has been neglected by growers, resulting in growing loss and consequent productivity and quality decreases in the final product (Farias et al., 2009). In order to irrigate more extensive areas with the available water resources, such factors as soil, plant, and water resource must be taken into consideration. In addition, the values of plant water consumption under either sufficient or deficient water conditions should be known throughout the growing season of plants and water-yield relationships should be formed accordingly. These data can be obtained by making a large number of investigations for each plant (Doorenbos and Kassam, 1979). To generate the data concerned, Conover (1969), Parnell (1989), Kiehl et al. (1992), Schuch et al. (1998), Rego et al. (2004), Fernandes et al. (2006), Budiarto et al. (2007), Farisa et al. (2009), Waterland et al. (2010) and Villalabos (2014) made investigations on irrigation and flower quality in the chrysanthemum plant. The majority of the investigations concerned are in the form of pot studies, and they are studies in


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which the plant quality was determined in different soil moisture tensions. Unlike the above-mentioned studies, this study aimed to determine the effects of different irrigation intervals and water amounts on yield and quality parameters in the chrysanthemum plant under greenhouse conditions in the Mediterranean climatic zone.

Among the water management practices for increasing WUE, there are several practices, one of them being mulching. Different types of materials such as straw, plastic film, grass, hyacinth, gravel, sand etc. are used as mulches. Mulching contributed to the crop production by influencing soil productivity; weed control, etc., depending upon the type of mulches (Asiegbu 1991). In addition, drip irrigation increases the yield of crops even at reduced irrigation water application (Yohannes and Tadesse 1998). The use of polyethylene mulch with drip irrigation in chrysanthemum production was reported to high yield and net income (Jawaharlal *et al*., 2017). In Bangladesh, chrysanthemum is gaining importance day by day for it's demand and commercial value. But still there is a lack of standard research work on water management and use of mulches to produce quality chrysanthemum. Hence, an attempt was made to investigate the performance of drip irrigation in conjunction with mulches for growth and flowering of chrysanthemum as cut flower.

*Objectives:*

- To find out the optimum irrigation scheduling and mulches for Chrysanthemum production.
- To evaluate the feasibility of drip irrigation with different mulches for Chrysanthemum cultivation in terms of growth and flowering of Chrysanthemum.

## Materials and Methods

The experiment was conducted during the winter season of 2020-2021 and 2021-2022 at the experimental field of IWM Division, BARI, Gazipur. The soils were silty clay loam with field capacity (28.5-29%), and bulk density (1.44-1.48) gm/cc.The experiment was laid out in a RCBD design with four replications. Nine treatments were designed for the experiment as stated below:

$T_1$ = Drip irrigation at 100% $ET_0$ with no mulch

$T_2$ = Drip irrigation at 100% $ET_0$ with black plastic mulch

$T_3$ = Drip irrigation at 100% $ET_0$ with paddy straw mulch

$T_4$ = Drip irrigation at 80% $ET_0$ with no mulch

$T_5$ = Drip irrigation at 80% $ET_0$ with black plastic mulch

$T_6$ = Drip irrigation at 80% $ET_0$ with paddy straw mulch

$T_7$ = Drip irrigation at 60% $ET_0$ with no mulch

$T_8$ = Drip irrigation at 60% $ET_0$ with black plastic mulch

$T_9$ = Drip irrigation at 60% $ET_0$ with paddy straw mulch

The unit plot size was 1.8 m × 1.5 m, with 1.5m wide buffer strip between plots to restrict seepage from neighboring plots. Recommended dose of fertilizers were applied @ 500 kg TSP, 160 kg MoP and cow-dung 8 t/ha. After one month of planting, urea @ 300kg and MoP @ 160kg were applied as top dressed. Besides, urea @ 100kg/ha was applied just after 1$^{st}$ pinching for better results. Seedling of chrysanthemum were used as the plant material in the research. Uniform rooted cuttings were planted on 02 December 2021 into plots with five rows 30×30 cm spacing and each plot contained 30 plants. Standard cultivation practices for flower bud removal, supporting system, disease and pest control as used for commercial chrysanthemum production were employed for growing the crops during the experiment. The practice of pinching was not applied to the plants in the study.

Soil moisture and temperature at every 10days interval was measured. Three plants were selected randomly and tagged in each plot for analysis of growth and flower yield characters viz. plant height, number of branches, number of bud, number of flower, date of bud initiation, date of bud burst, date of full blooming, stem length, flower diameter and various other similar characters. Data of the investigation is presented in the Table 1.

Irrigations were done in drip irrigation method with three mulches as per treatments. The drippers having a discharge of 4 l h-1 at a pressure of 0.1 MPa on laterals were located 30 cm apart. The dripper were arranged in such a way that every lateral had six drippers with 30 cm intervals. The amount of irrigation water applied in the treatments was controlled by using a gauge on the main pipeline and valves located on each lateral. The irrigation water to be applied was calculated by the equation given below.

$$I = P_c \text{ x } E_{pan} \times A \times P \quad (1)$$

where, I is the irrigation water (mm), $P_c$ is the pan coefficient, $E_{pan}$ is the cumulative pan evaporation (mm), A is the plot area ($m^2$) and P is the wetted area percentage (%). The wetted area was taken as 100% assuming that lateral interval is equal to the spaces between drippers.

All the water which evaporated from Class A Pan (CAP) for 25 days after planting (DAP) was applied equally to all the treatments as irrigation water to ensure the root development and full survival of seedlings. The application of different irrigation water amounts was initiated 25 days after planting (DAP).

For mulching, 10 t/ha paddy straw was used after 7 days of transplanting. For black polyethylene mulch, 10 μm black polyethylene sheet having holes of 50 mm diameter at a distance of 30 cm × 30 cm was spread over the beds and chrysanthemum seedlings were transplanted in the holes. Undesirable plants were rouged out. The flowers were harvested from February 06, 2021 to February 30, 2021 when the flower in the middle opened completely and the surrounding flowers displayed full development.

## Results and discussions

### *Plant growth and floral characters*

Growth and flowering parameters of chrysanthemum as affected by irrigation level and mulching are presented on Table 1. It was observed that treatment with most intensive irrigation with black plastic (T2) and straw mulch (T3) exhibited better performance for all parameters except days to flower blooming, flower diameter and flower duration. However, the lowest results were determined in treatment (T7) for all parameters that was statistically significant with the highest one.

As shown in Figure 1, black plastic mulch and paddy straw mulch resulted in taller plant as compared to no mulch at all irrigation amount treatments. During 20-21, since the start of sowing to 50 days, the highest plant height was achieved from treatment $T_1$. After that from 60 days, clear and significant differences were observed between all the other curves. During 21-22, significant differences among the treatments were observed from 40 days after sowing. It might be due to the heavy rainfall that was occurred at 4 th December, 2022.The bar charts for black polythene and paddy straw mulch with 100% $ET_0$ were almost indistinguishable both the two years. Overall, plant covered by black polythene and paddy straw mulch with 80% $ET_0$ were significantly comparable with the no mulch treatment with 100% $ET_0$. And no mulch and other mulches treatment with 60% $ET_0$ were significantly comparable with the no mulch treatment with 80% $ET_0$. This may be due to the moisture stress conditions present for plants grown under no mulch with 80% $ET_0$ irrigation amount and all mulches with the lowest irrigation amount.

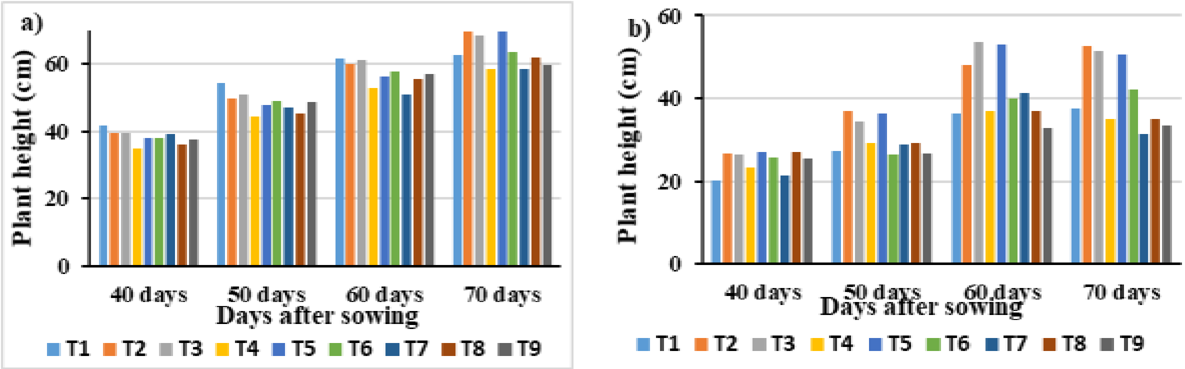



Fig. 1. Effect of different irrigation treatments with different mulching on plant height at different days after sowing during 2020-21 (a) and 2021-22 (b).

During 2020-21, the highest number of leaves (251) was resulted from treatment $T_5$ (drip irrigation at 80% $ET_0$ with black plastic mulch) followed by treatment ($T_6$) and during 21-22 the highest number of leaves (238) was achieved from treatment $T_2$ followed by $T_3$, $T_5$ and $T_6$. Whereas, the lowest number of leaves (160.44 and 109.86) was obtained from treatment $T_4$ (drip irrigation at 80% $ET_0$ with no mulch) and $T_7$ (drip irrigation at 60% $ET_0$ with no mulch) respectively during the two years, that was statistically significant with the highest one. The burst bud diameter was non-significant (p=0.05) in both the two years.

Table 1.a. Effect of drip irrigation levels and mulching on growth and flowering parameters of chrysanthemum plant and flower during 20-21

| Treatments | No. of leaves | | Days to bud initiation | | Days to bud burst | | Burst bud diameter (cm) | | Days to flower blooming | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 20-21 | 21-22 | 20-21 | 21-22 | 20-21 | 21-22 | 20-21 | 20-21 | 20-21 | 21-22 |
| $T_1$ | 205.00 | 175.98 | 36.89 | 36.48 | 17.21 | 17.39 | 0.18 | 0.18 | 12.62 | 13.67 |
| $T_2$ | 209.78 | 238.47 | 37.67 | 37.91 | 18.49 | 18.35 | 0.19 | 0.18 | 15.34 | 14.17 |
| $T_3$ | 210.89 | 226.66 | 37.60 | 37.77 | 18.46 | 18.15 | 0.19 | 0.18 | 14.96 | 14.00 |
| $T_4$ | 160.44 | 167.00 | 36.32 | 36.26 | 16.99 | 17.05 | 0.18 | 0.18 | 12.10 | 13.00 |
| $T_5$ | 251.78 | 231.50 | 36.47 | 36.96 | 17.80 | 17.67 | 0.19 | 0.18 | 13.51 | 13.17 |
| $T_6$ | 248.45 | 223.49 | 37.11 | 36.98 | 18.07 | 18.04 | 0.19 | 0.18 | 13.30 | 13.83 |
| $T_7$ | 166.11 | 109.86 | 36.20 | 35.69 | 15.78 | 16.02 | 0.18 | 0.18 | 11.89 | 12.33 |
| $T_8$ | 171.22 | 131.41 | 36.44 | 36.20 | 17.09 | 16.84 | 0.18 | 0.18 | 12.40 | 12.67 |
| $T_9$ | 204.56 | 144.29 | 36.42 | 36.27 | 17.08 | 16.95 | 0.19 | 0.18 | 12.16 | 12.72 |
| CV (%) | 16.98 | 13.03 | NS | 1.45 | 2.37 | 1.85 | NS | NS | 8.88 | 4.51 |
| LSD (0.05) | 9.69 | 7.64 | - | 0.92 | 0.71 | 0.56 | - | - | 2.02 | 1.04 |

While, floral characters like days to bud initiation, bud burst, flower blooming and flower destroy were greatly influenced by irrigation levels and mulching. Bud initiation, burst, blooming and destroy of chrysanthemum plants grown on mulch was a little delayed. Black polythene and straw mulch with the most intensive irrigation were statistically par with each other, reaching 50% primary bud initiation/plot and bud burst/plot. Whereas, those treatments were also comparable with black polythene and straw mulch treatments with 80% $ET_0$ and no mulch treatments with 100% $ET_0$. On the other hand, no mulch treatments with 80% and 60% $ET_0$ need lower time for reaching 50% primary bud initiation/plot, bud burst/plot, flower blooming/plot and flower destroy/plot. They were statistically par with each other and comparable with the treatments black polythene and straw mulch with 60% ET0. It might be due to; no mulch with 60% $ET_0$ or 80% $ET_0$ irrigation water seems too little to provide adequate moisture to plants to maintain normal growth and this water deficit condition promotes plant to shorten their life cycle. Yuri Shavrukov et al., 2017, R.G. Sharp, 2008 and J.

Cuevas et al., 2008 reported the same observations for different crops. Though, black plastic mulch and paddy straw mulch with 100% and 80% $ET_0$ were significantly similar for bud initiation and burst, but not for flower blooming and destroying. Black plastic mulch with 100% $ET_0$ need more time for flower blooming but less time for flower destroying. The possible reason could be that soil moisture and temperature was rising during the crop growing period day by day beneath the black polythene mulch. This situation possibly negatively affected the nutrient uptake facilities at the root zone for the chrysanthemum plants to survive. Flowers were getting smaller in size and finally burned. However, straw mulch with 100% $ET_0$ was comparable with black plastic and straw mulch treatments with 80% $ET_0$ and no mulch treatments with 100% $ET_0$, reaching 50% flower blooming/plot and destroy/plot.

Number of branches and number of bud were significantly varied among different mulches or irrigation amount (fig. 2). The highest number of branches and number of buds were obtained from treatment $T_2$ followed by treatment $T_3$, $T_5$ and $T_6$, whereas the lowest number of bud was obtained from treatment $T_7$ which was significantly par with treatment $T_4$. Finally, no mulch treatment with 80% and 60% $ET_0$ and black polythene and paddy straw mulch with 60% $ET_0$ did not do well for number of branch and bud initiation at both the two years.

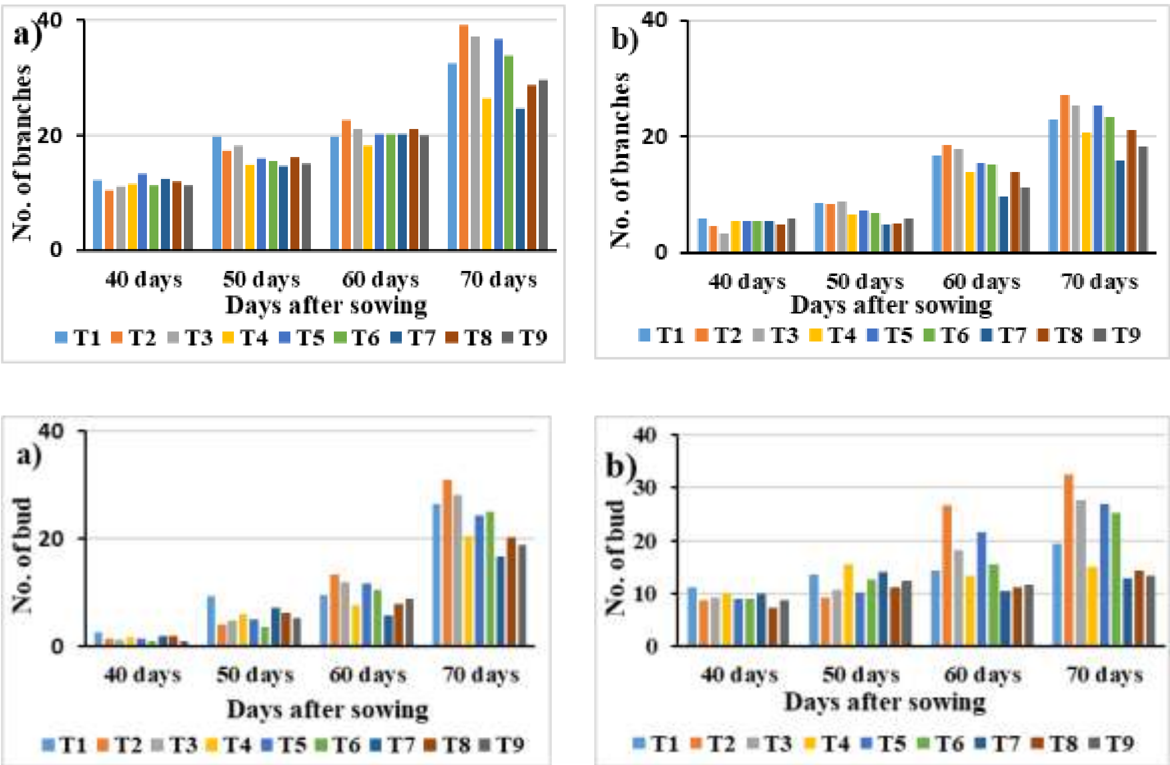



Fig. 2. Effect of different irrigation treatments with different mulching on number of branches and number of buds at different days after sowing during 2020-21 (a) and 2021-22 (b).

During the two years, maximum flower diameter was achieved from treatment $T_3$ was statistically similar with the treatments $T_1$, $T_5$ and $T_6$. And during these two years, the treatment $T_2$ exhibited better performance for stem length (33.03 cm and 45.67), number of flower per branch (4.95 and 6.30) and number of flowers/plant (38.33 and 33.00) which were statistically comparable with the treatment ($T_3$). However, the lowest flower diameter (9.33 cm and 9.44 cm), stem length (25.36 cm and 30.33 cm), number of flower/branch (2.72 and 2.70) and number of flowers/plant (19.11and 14.83) were determined in treatment ($T_7$) followed by treatments $T_8$ and $T_9$.

Table 1.b. Effect of drip irrigation levels and mulching on growth and flowering parameters of chrysanthemum plant and flower during 20-21

| Treatments | Flower diameter (cm) | | Stem length (cm) | | No. of flower/ branch | | No. of flowers/ plant | |
|---|---|---|---|---|---|---|---|---|
| | 20-21 | 21-22 | 20-21 | 21-22 | 20-21 | 21-22 | 20-21 | 21-21 |
| $T_1$ | 10.56 | 10.33 | 3.38 | 4.10 | 3.38 | 4.10 | 28.22 | 20.00 |
| $T_2$ | 9.78 | 10.11 | 4.95 | 6.30 | 4.95 | 6.30 | 38.33 | 33.00 |
| $T_3$ | 11.11 | 11.00 | 4.87 | 5.50 | 4.87 | 5.50 | 37.66 | 29.83 |
| $T_4$ | 9.89 | 10.11 | 3.07 | 3.90 | 3.07 | 3.90 | 20.74 | 17.5 |
| $T_5$ | 10.89 | 10.48 | 3.69 | 5.40 | 3.69 | 5.40 | 35.11 | 27.00 |
| $T_6$ | 10.50 | 10.24 | 3.60 | 4.70 | 3.60 | 4.70 | 33.02 | 26.17 |
| $T_7$ | 9.33 | 9.44 | 2.72 | 2.70 | 2.72 | 2.70 | 19.11 | 14.83 |
| $T_8$ | 9.45 | 9.66 | 3.16 | 3.60 | 3.16 | 3.60 | 21.56 | 16.50 |
| $T_9$ | 9.67 | 9.89 | 3.23 | 3.50 | 3.23 | 3.50 | 21.57 | 16.33 |
| CV (%) | 3.09 | 4.77 | 13.41 | 11.20 | 13.41 | 8.66 | 9.45 | 16.50 |
| LSD (0.05) | 0.55 | 0.76 | 0.78 | 1.49 | 0.78 | 3.52 | 4.43 | 4.43 |

The maximum marketable branches/10m2 (875.56 and 744.44) was achieved with the treatment $T_3$(drip irrigation at 100% $ET_0$ with paddy straw mulch) which was significantly par with the treatment $T_5$ (814.44, 648.89) and $T_6$ (756.67 and 616.67) (drip irrigation at 80% $ET_0$ with black plastic and paddy straw mulch) (table 1.c). And the minimum marketable branches/10m2 (271.11and 208.89) was achieved with the treatment ($T_7$) (drip irrigation at 60% $ET_0$ with no mulch). But, the highest number of marketable flower per branch (8.00 and 6.70) was obtained from treatment $T_3$ followed by treatment $T_5$ and $T_6$. And the lowest number of flower/ marketable branch (4 and 4.01) and marketable branches/plant (2.44 and 2.09) were obtained from treatment $T_7$.

Table 1.c. Effect of drip irrigation levels and mulching on growth and flowering parameters of chrysanthemum plant and flower during 20-21

| Treatments | Marketable branch/ plant | | Flowers/marketable branch | | Marketable branch/ 10m2 | | Days to flower destroy (in field) | |
|---|---|---|---|---|---|---|---|---|
| | 20-21 | 21-22 | 20-21 | 21-22 | 20-21 | 21-22 | 20-21 | 21-22 |
| $T_1$ | 6.67 | 4.51 | 4.55 | 4.18 | 741.11 | 501.11 | 13.64 | 13.85 |
| $T_2$ | 3.33 | 2.78 | 5.1 | 5.22 | 370.00 | 308.89 | 11.00 | 11.03 |
| $T_3$ | 7.88 | 6.70 | 4.87 | 4.82 | 875.56 | 744.44 | 15.34 | 15.17 |
| $T_4$ | 5.33 | 4.42 | 4.33 | 4.15 | 592.22 | 491.11 | 12.39 | 13.04 |
| $T_5$ | 7.33 | 5.94 | 4.55 | 4.60 | 814.44 | 648.89 | 14.14 | 14.22 |
| $T_6$ | 6.81 | 5.35 | 4.45 | 4.52 | 756.67 | 616.67 | 14.03 | 14.41 |
| $T_7$ | 2.44 | 1.88 | 4 | 4.01 | 271.11 | 208.89 | 11.14 | 11.33 |
| $T_8$ | 2.75 | 2.86 | 4.11 | 4.13 | 305.56 | 317.78 | 13.00 | 12.07 |
| $T_9$ | 3.13 | 2.09 | 4.22 | 4.10 | 347.78 | 232.22 | 12.61 | 12.20 |
| CV (%) | 4.43 | 3.12 | 8.37 | 9.15 | 4.45 | 5.57 | 4.85 | 7.33 |
| LSD (0.05) | 3.66 | 0.79 | 0.86 | 2.41 | 3.52 | 4.40 | 0.55 | 2.92 |

Plant fresh weight and dry weight were highly significant with irrigation amount and mulches. The highest plant fresh weight and dry weight was recorded in treatment $T_2$ which was very close to treatment $T_3$ and $T_1$. And the lowest was recorded from no mulch treatment of $T_7$ (Fig. 3) followed by treatment $T_4$ and $T_9$. This result confirms that the plants grown with low irrigation amount influenced plant biomass production highly. It may be due to, plant experienced with moisture stress produce lower biomass.

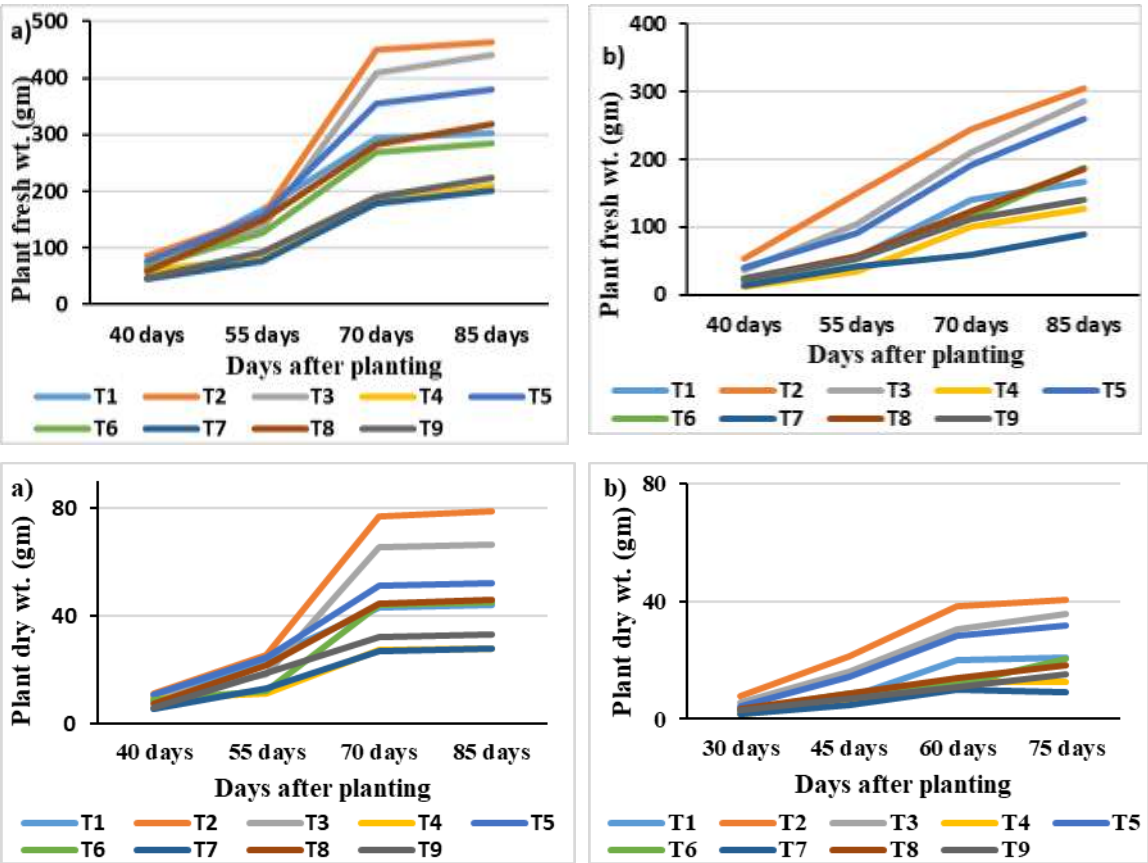



Fig. 3. Effect of different irrigation treatments with different mulching on plant fresh weight and plant dry weight at different days after sowing during 2020-21 (a) and 2021-22 (b).

Both irrigation amount and mulches influenced the root length, root fresh weight and dry weight (Figure 4). Increasing irrigation amount with mulches decreased root length, fresh weight and dry weight. The highest root length was found in low irrigation applied treatments $T_7$ where mulching was absent. Lower root length was found in mulching treatments $T_2$, $T_3$, $T_5$, $T_6$ and no mulch treatment $T_1$, might be due to getting adequate moisture to the root zone.

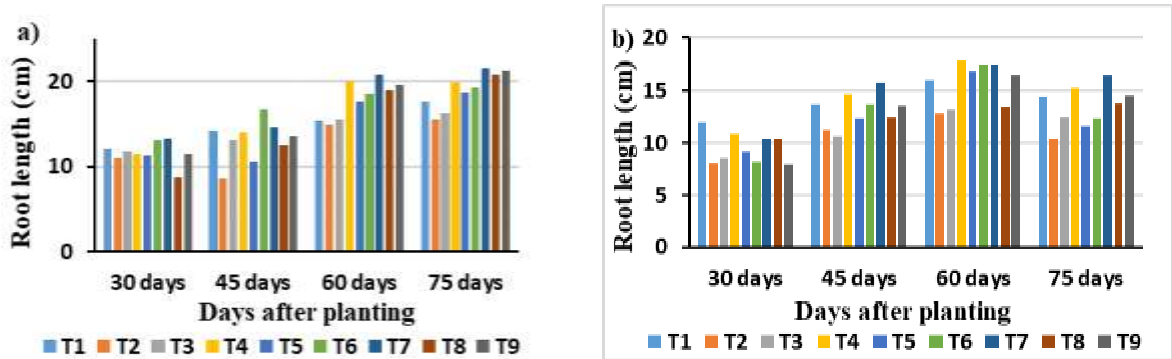



Fig. 4. Effect of different irrigation treatments with different mulching on root length at different days after sowing during 2020-21 (a) and 2021-22 (b).

However, the highest root fresh weight and dry weight was found in treatment $T_1$ (irrigation was given at 100% $ET_0$ with no mulch). Furthermore, Among the irrigation amount treatments, black plastic mulch showed the lowest root fresh weight and dry weight and ultimately the lowest root to shoot ratio, as plant fresh weight and dry weight was high (figure-3). And considering mulching, irrigation with 60% $ET_0$ showed the lowest result for root fresh weight and dry weight and higher root to shoot ratio.

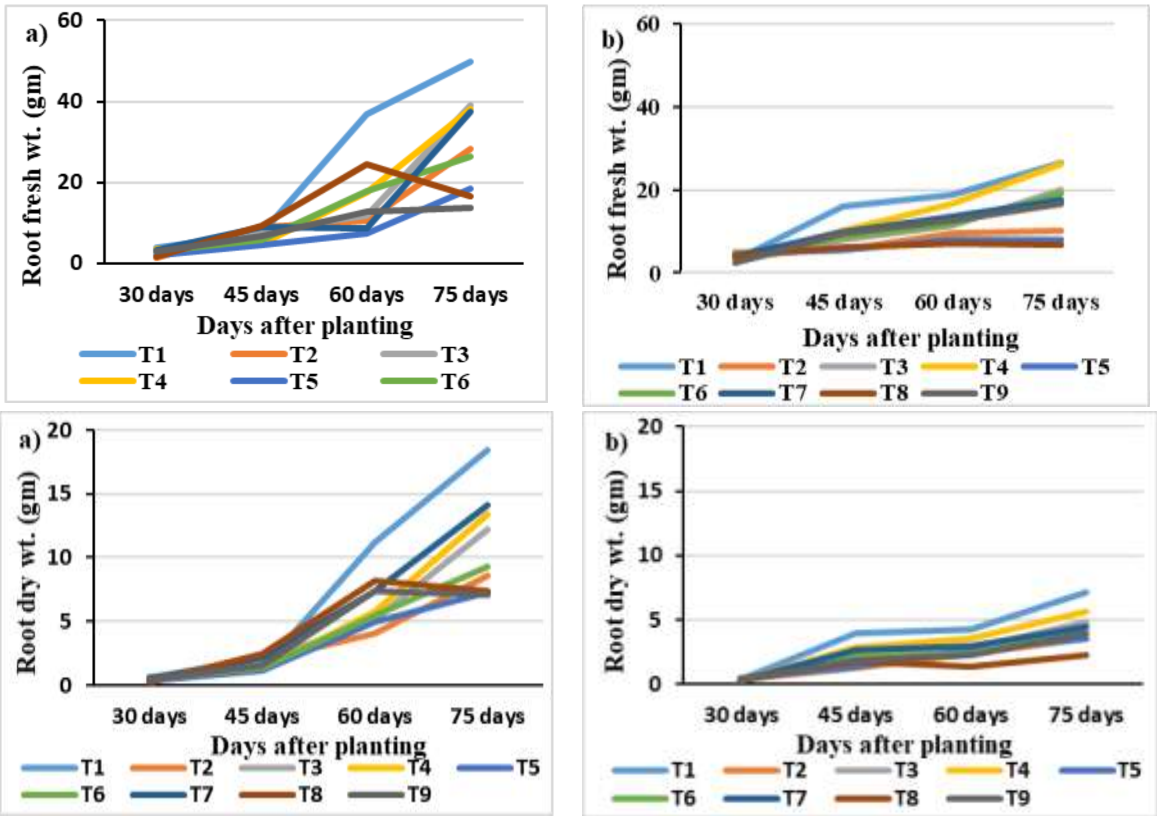



Fig. 5. Effect of different irrigation treatments with different mulching on root fresh weight and root dry weight at different days after sowing during 2020-21 (a) and 2021-22 (b).

However, root to shoot ratio increased from black plastic mulch to paddy straw mulch to no mulch treatments. Approximate reason for that, mulch creates excess moisture beneath the plastic or paddy straw which tended to lower the root volume and length to the soil. Besides, excess moisture pronounced plant vegetation greatly, ultimately lower root to shoot ratio. Treatment $T_2$ was highly moisturized due to black plastic mulch. As a results, it showed the lowest root length, root fresh weight and dry weight and root to shoot ratio.

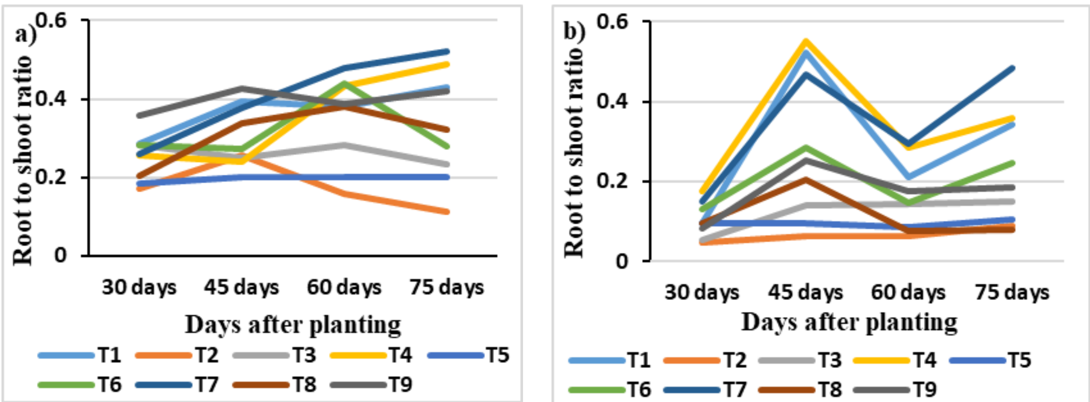



Fig. 6. Effect of different irrigation treatments with different mulching on root to shoot ratio at different days after sowing during 2020-21 (a) and 2021-22 (b).

## *Weed growth*

Table 2. revealed that black plastic mulch hampered weed growth effectively. But paddy straw mulch was more vulnerable for weed growth than black plastic mulch. No of weeds, weed fresh weight (gm) and dry weight (gm) were significantly varied with mulching. Maximum no of weeds, weed fresh weight (gm) and dry weight (gm) were obtained from no mulch. And minimum no of weeds, weed fresh weight (gm) and dry weight (gm) were obtained from black plastic mulch treatments. Pritee

Awasthy et al.,2014 also found the same results that the black plastic mulch increased maize yield by controlling weed growth.

Table 2. Effect of irrigation levels and mulching on weed growth

| Treatments | No of weeds | | Fresh weight (gm) | | Dry weight (gm) | |
|---|---|---|---|---|---|---|
| | 20-21 | 21-22 | 20-21 | 21-22 | 20-21 | 21-22 |
| $T_1$ | 53.00 | 92.67 | 121.83 | 254.21 | 14.92 | 39.78 |
| $T_2$ | 10.00 | 13.00 | 20.50 | 29.6 | 4.96 | 4.33 |
| $T_3$ | 20.00 | 31.00 | 29.10 | 22.86 | 4.80 | 16.01 |
| $T_4$ | 66.67 | 90.33 | 134.22 | 220.5 | 15.01 | 37.88 |
| $T_5$ | 17.00 | 9.00 | 47.87 | 11.97 | 6.99 | 2.46 |
| $T_6$ | 41.00 | 69.33 | 31.36 | 104.55 | 5.55 | 80.60 |
| $T_7$ | 59.67 | 86.67 | 69.60 | 187.74 | 10.23 | 36.53 |
| $T_8$ | 18.00 | 7.67 | 17.85 | 15.32 | 4.08 | 2.32 |
| $T_9$ | 42.00 | 34.00 | 30.32 | 27.44 | 5.78 | 16.58 |
| CV(%) | 13.00 | 12.00 | 12.83 | 13.4 | 12.92 | 10.03 |
| LSD(0.05) | 6.00 | 19.48 | 6.50 | 14.26 | 4.96 | 6.88 |

### *Amount of irrigation water and water use*

During 20-21, at the start of the experiment, 33 mm irrigation water was applied for about 25 days to no mulch experimental plots and 20 mm for mulching experimental plots to avoid any problems in the plant establishment. After the completion of plant establishment, irrigation water was applied to the experimental plots according to the designed treatments. The amount of irrigation water based on the treatments was initiated on 25 December 2020 and ended on 27 February 2021. The amount of water applied to the crop ranged from 177.58 mm and 219.94 mm with minimum in the 60% $ET_0$ treatment and maximum in the wettest treatment of 100% $ET_0$ (Table 3) respectively. Among the all treatments, the highest water productivity was 35.77 kg/m3 obtained from treatment $T_5$, as it was one of the treatment of higher yield with lower water consumption. Similar observation was found by Maheria et al. (2013). Total water used for no mulch treatments were ranged from 185.78 to 222.01 mm, for black plastic mulch from 172.16 to 207.67 mm and for paddy straw mulch from 172.39 to 207.84 mm at all irrigation amount treatments. The lowest water productivity was achieved with treatment $T_7$ as this treatment yielded minimum.

Table 3. a. Irrigation water use and water productivity in different treatments during the year 20-21

| Treat ment | Number of Irrigation applied | Dripper dischar ge (l/h) | Water for plant establish me-nt (mm) | Irrigatio n water applied (mm) | Effectiv e rainfall (mm) | Soil moisture contribution (mm) | Total water Use (mm) | Water productiv ity (kg/m3) |
|---|---|---|---|---|---|---|---|---|
| $T_1$ | 21 | 4 | 33 | 93 | 95.6 | 0.41 | 222.01 | 20.44 |
| $T_2$ | 21 | 4 | 20 | 93 | 95.6 | -0.93 | 207.67 | 24.59 |
| $T_3$ | 21 | 4 | 20 | 93 | 95.6 | -0.76 | 207.84 | 34.94 |
| $T_4$ | 21 | 4 | 33 | 74.4 | 95.6 | 0.49 | 203.49 | 13.25 |
| $T_5$ | 21 | 4 | 20 | 74.4 | 95.6 | 0.02 | 190.02 | 35.77 |
| $T_6$ | 21 | 4 | 20 | 74.4 | 95.6 | -0.45 | 189.55 | 23.18 |
| $T_7$ | 21 | 4 | 33 | 55.8 | 95.6 | 1.38 | 185.78 | 12.42 |
| $T_8$ | 21 | 4 | 20 | 55.8 | 95.6 | 0.76 | 172.16 | 16.54 |
| $T_9$ | 21 | 4 | 20 | 55.8 | 95.6 | 0.99 | 172.39 | 16.21 |

During 21-22, at the start of the experiment, only 10 mm of irrigation water was applied for plant establishment as heavy rainfall was occurred at 04-12-22 after sowing. After the completion of plant establishment, irrigation water was applied to the experimental plots according to the designed treatments. The amount of irrigation water based on the treatments was initiated on 27 December

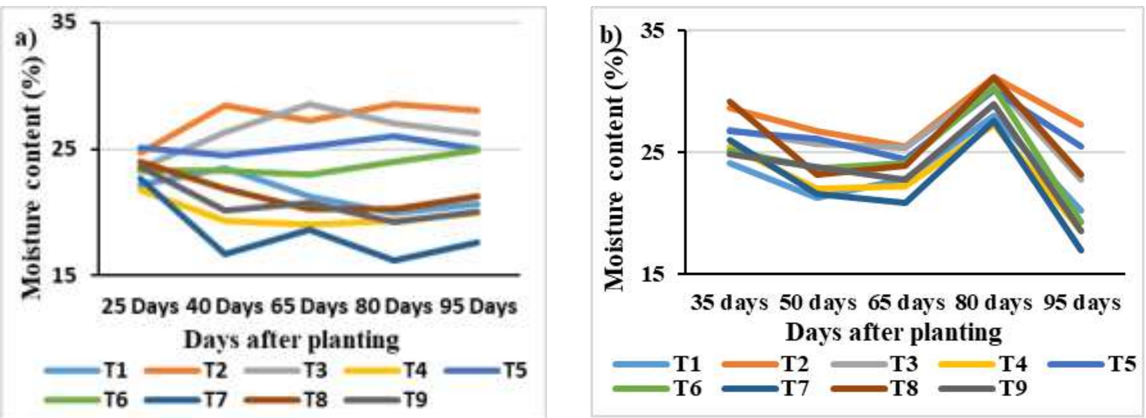
2020 and ended on 02 March 2022. The amount of water used by the crop ranged from 173.34 mm and 207.80 mm with minimum in the 60% $ET_0$ treatment and maximum in the wettest treatment of 100% $ET_0$ (Table 3) respectively. Among the all treatments, the highest water productivity was 29.97 kg/m3 obtained from treatment $T_3$, as it was the highest yielded treatment. Total water used for no mulch treatments were ranged from 173.35 to 207.75 mm, for black plastic mulch from 173.52 to 207.87 mm and for paddy straw mulch from 173.34 to 207.80 mm at all irrigation amount treatments. The lowest water productivity was achieved with treatment $T_7$ as this treatment yielded minimum. It can be said that, an appropriate mulching method with optimum irrigation water can increase flower yield ultimately water productivity by continuously maintaining moist soil around plant roots.

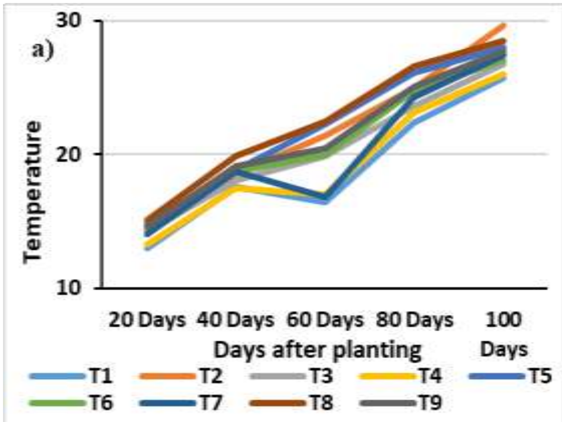
Table 3. b. Irrigation water use and water productivity in different treatments during the year 21-22

| Treatment | Number of Irrigation applied | Dripper discharge (l/h) | Water for plant establishme-nt (mm) | Irrigation water applied (mm) | Effective rainfall (mm) | Soil moisture contribution (mm) | Total water Use (mm) | Water productivity (kg/m3) |
|---|---|---|---|---|---|---|---|---|
| $T_1$ | 11 | 4 | 10 | 68.56 | 128.11 | 1.08 | 207.75 | 13.03 |
| $T_2$ | 11 | 4 | 10 | 68.56 | 128.11 | 0.37 | 207.04 | 20.70 |
| $T_3$ | 11 | 4 | 10 | 68.56 | 128.11 | 1.13 | 207.80 | 29.97 |
| $T_4$ | 11 | 4 | 10 | 50.29 | 128.11 | 1.91 | 190.31 | 9.57 |
| $T_5$ | 11 | 4 | 10 | 50.29 | 128.11 | 0.34 | 188.74 | 25.02 |
| $T_6$ | 11 | 4 | 10 | 50.29 | 128.11 | 1.63 | 190.03 | 22.52 |
| $T_7$ | 11 | 4 | 10 | 33.74 | 128.11 | 1.50 | 173.35 | 5.67 |
| $T_8$ | 11 | 4 | 10 | 33.74 | 128.11 | 1.67 | 173.52 | 8.47 |
| $T_9$ | 11 | 4 | 10 | 33.74 | 128.11 | 1.49 | 173.34 | 9.62 |

### *Soil moisture and temperature*

The figure 7 revealed that soil temperature was increased in black plastic mulch to some extent (fig:3b). But whenever it irrigated properly then temperature tend to become low. Same observation was reported by Tariq et al. and Diaz-Perez et al. that sufficient amount of moisture content and temperature ensure quality chrysanthemum flower. The figure 7 showed that before irrigation started, soil moisture was found to be almost similar for all the treatments. But with the passing time, there were great variations among them. The highest moisture content was found from treatment $T_2$ followed by treatment $T_3$. The lowest moisture content was found from treatment $T_7$ followed by treatment $T_8$ and $T_9$. It was found that soil temperature of treatment $T_8$ was higher than other treatment, but soil moisture trend was found comparatively lower. However, the lower soil temperature was recorded in no mulch treatments ($T_1$, $T_4$, $T_7$) during the cropping period. It can be said that continuous higher moisture content and temperature beneath the black plastic mulch create an unfavorable weather for plant at the last of growing period with 100% $ET_0$ of irrigation. Hence, though the plant was always vigorous and healthy it could not give marketable flower lastly.





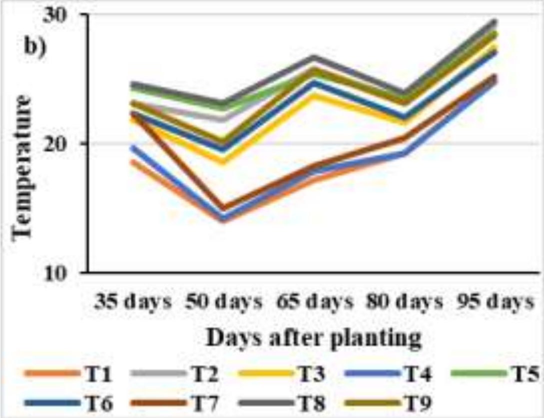



Fig. 7. Effect of different irrigation treatments with different mulching on soil moisture content and temperature during 2020-21 (a) and 2021-22 (b).

***Economic analysis***

Table 4. (a,b) showed economic analysis of chrysanthemum production with different amount of irrigation and different types of mulching. In both the two years, the highest BCR (6.09 and 5.18) was obtained from treatment $T_3$ which was almost similar (6.04 and 4.81) to treatment $T_5$. For the reason that, treatment $T_3$ yielded little bit higher than treatment $T_5$, but, it used lower labor wage and irrigation water. Both the two treatments were also comparable with the treatment $T_6$, as it was also used lower labour and irrigation water with comparatively higher yield. The lowest BCR (1.99 and 1.54) was obtained from treatment $T_7$ both the two years.

Table 4.a. economic analysis of chrysanthemum, 20-21

| Treat ments | Market able branch/ ha | Selling rate (Tk/bran ch) | Gross return (tk) | Total fixed cost/year | Total variable cost/year | Total cost/year | Net return | BCR |
|---|---|---|---|---|---|---|---|---|
| $T_1$ | 740741 | 20 | 14814815 | 1450000 | 1635802 | 3085802 | 13179012 | 4.80 |
| $T_2$ | 370370 | 20 | 7407407 | 1450000 | 1432099 | 2882099 | 5975309 | 2.57 |
| $T_3$ | 874074 | 20 | 17481481 | 1450000 | 1422222 | 2872222 | 16059259 | 6.09 |
| $T_4$ | 592593 | 20 | 11851852 | 1450000 | 1450617 | 2900617 | 10401235 | 4.09 |
| $T_5$ | 814815 | 20 | 16296296 | 1450000 | 1246914 | 2696914 | 15049383 | 6.04 |
| $T_6$ | 755556 | 20 | 15111111 | 1450000 | 1237037 | 2687037 | 13874074 | 5.62 |
| $T_7$ | 270370 | 20 | 5407407 | 1450000 | 1265432 | 2715432 | 4141975 | 1.99 |
| $T_8$ | 307407 | 20 | 6148148 | 1450000 | 1061728 | 2511728 | 5086420 | 2.45 |
| $T_9$ | 348148 | 20 | 6962963 | 1450000 | 1051852 | 2501852 | 5911111 | 2.78 |

Table 4.b. economic analysis of chrysanthemum, 21-22

| Treat ments | Market able branch/ ha | Selling rate (Tk/bran ch) | Gross return (tk) | Total fixed cost/year | Total variable cost/year | Total cost/year | Net return | BCR |
|---|---|---|---|---|---|---|---|---|
| $T_1$ | 501111 | 20 | 10022222 | 1450000 | 1635802 | 3085802 | 8386420 | 3.25 |
| $T_2$ | 308889 | 20 | 6177778 | 1450000 | 1432099 | 2882099 | 4745679 | 2.14 |
| $T_3$ | 744444 | 20 | 14888889 | 1450000 | 1422222 | 2872222 | 13466667 | 5.18 |
| $T_4$ | 491111 | 20 | 9822222 | 1450000 | 1450617 | 2900617 | 8371605 | 3.39 |
| $T_5$ | 648889 | 20 | 12977778 | 1450000 | 1246914 | 2696914 | 11730864 | 4.81 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| $T_6$ | 616667 | 20 | 12333333 | 1450000 | 1237037 | 2687037 | 11096296 | 4.59 |
| $T_7$ | 208889 | 20 | 4177778 | 1450000 | 1265432 | 2715432 | 2912346 | 1.54 |
| $T_8$ | 317778 | 20 | 6355556 | 1450000 | 1061728 | 2511728 | 5293827 | 2.53 |
| $T_9$ | 232222 | 20 | 4644444 | 1450000 | 1051852 | 2501852 | 3592593 | 1.86 |

## Conclusion

It was observed that chrysanthemum flower significantly influenced with irrigation level and mulching system. Black plastic mulch was superior over paddy straw mulch and no mulching system for 100% $ET_0$ for all parameters except marketable production. However, all commercial variables evaluated showed significantly higher values in drip irrigation at 100% $ET_0$ with paddy straw mulch. Still, depending upon the local water convenience and pursuing maximization of farmer's revenue, the 80% $ET_0$ of irrigation level with black plastic mulch or paddy straw mulch system can be considered advantageous. Higher levels of water deficit imply a lower plant life cycle with reduced yield, resulting a potential economic damage to the farmers.

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# PERFORMANCE OF FERTIGATION SYSTEM ON PUMPKIN CULTIVATION

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## Abstract

An experiment was conducted at the research field of Irrigation and water Management (IWM) Division, Bangladesh Agricultural Research Institute (BARI), Joydebpur, Gazipur during the rabi season of 2020-21 and 2021-22 to determine the performance of pumpkin (var. BARI Hybrid Mistikumra-1) under fertigation systems. Six different irrigation treatments $T_1$= Ring Basin irrigation at 7 days interval with recommended fertilizer doses, $T_2$= Fertigation at an alternate day with recommended fertilizer doses, $T_3$= Fertigation at an alternate day with 20% less N and K than recommended doses, $T_4$= Fertigation at an alternate day with 35% less N and K than recommended doses, $T_5$= Fertigation at an alternate day with 50% less N and K than recommended doses were selected. The highest yield of 32.41 t/ha was obtained from treatment $T_4$ by applying 35% less N and K than recommended doses through drip system followed by treatment $T_3$ (30.71 t/ha) by applying 20% less N and K than recommended doses through drip system. Ring basin method required 413 mm of water during the season whereas only 241 mm water was needed in drip method. The economic analysis revealed that the highest benefit cost ratio (2.60) was obtained from treatment $T_4$ by applying 35% less N and K than recommended doses through drip system followed by treatment $T_3$ (2.48) by applying 20% less N and K than recommended doses through drip system. This is the first year results, so the experiment should be continued for the next year.


## Introduction

Global fruit and vegetable production has increased to 1.34 billion MT in 2003, up from 396 million MT in 1961 (FAO, 2005). Vegetable production is usually lucrative compared to staple crops. Therefore, a relatively large body of the literature deals with poverty outcomes for small farmers from opportunities represented through horticultural trade (Dolan and Humphrey, 2000; Henson et al., 2005, Maertens, 2006). Bottle gourd (Lagenaria siceraria L.) belongs to Cucurbitaceae family. It is characterized by trailing growth habit, branched tendril, male flowers appear first, fruits are pepo varying greatly in shapes, sizes and colors. It thrives well in hot and humid conditions. Higher temperature, long day length, and sun light render more male flowers. It can grow over a wide range of soils but sandy loam soil with good natural drainage and pH near 6.5 is desirable.

Pumpkin (Cucurbita moschata) is an important vegetable crop grown in all over the world. Considering its high nutritional content (vitamin, carbohydrate, mineral, fibre, antioxidant, and phytonutrient) (Aruah et al. 2010) and lucrative market value, this vegetable may be considered as a high value crop (Rahman et al. 2013). Pumpkin is also known as a less water consuming crop. Therefore, its survival ability under water stress condition could be explored to find out opportunities of cultivation in areas where irrigation water is scare. Currently, pumpkin is widely grown in char areas of Bangladesh, such as Lalmonirhat and Kurigram, where irrigation facility is scarce.

Pumpkin is a winter crop and it takes about five months for the fruits to get matured. Therefore, without proper irrigation management it is difficult to obtain reasonable yield of pumpkin.

Variety is an important characteristic that regulates yield and water requirement of crop. For high yielding variety, irrigation is very much essential during winter season to produce better yield in terms of quality and quantity (Bose et al. 1980). The frequency of irrigation in summer is very important but irrigation may not be necessary at all in summer for the crop if rainfall is well distributed between June and September. The role of irrigation at proper level and stages of plant growth has great significance in improving the yield (Singh et al., 1990). Padem and Alan (1992), Gupta (1990), Bandel et al. (1980), and Thomas et al. (1970) reported that judicious application of fertilizers in conjunction with proper irrigation is the principal factor affecting the crop yield. Modern


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farming systems have taken advantages of different sophisticated techniques of irrigation that are based either on assessment of soil moisture depletion or moisture tension. Irrigation, once in 5 to 6 days, may be necessary depending upon soil, location, temperature etc, and it is very much essential during winter season to produce better yield in terms of quality and quantity (Bose et al. 1980).

Fertigation is a modern technique and is widely used in many developed countries for horticultural crops. But it is not yet to practice widely in Bangladesh. Furrow and flood irrigation are being widely practiced here for papaya cultivation. The concept of fertigation is to create a continuous method strip along the lines of the plants. It increases the irrigation water and fertilizer use efficiency to a considerable extent and is especially used for high value horticultural crops. This technology saves both water and fertilizer and gives higher yield than any other method (Bresler, 1997). Fertigation in tomato gave encouraging results in terms of yield and economic return (Akanda *et al.*, 2004).

Several studies have been reported on drip irrigation of fruit crop in different countries of the world (Birbal *et al.*, 1998; Birbal *et al.*, 2003; Suresh and Kumar, 2007; Tan *et al.*, 2009). But, Information regarding drip irrigation of bottle gourd in the context of our country is not available. So, it is important to determine the performance of sweet gourd under fertigation systems in the context of our country for higher yield of bottle gourd. That is why; the present study was undertaken in the field of Irrigation and Water Management Division of Bangladesh Agricultural Research Institute, Joydebpur, Gazipur.

## Materials and Methods

The experiment was conducted on pumpkin (BARI Hybrid Mistikumra-1) in the field of Irrigation and Water Management Division of Bangladesh Agricultural Research Institute, Joydebpur, Gazipur.during rabi seasons of 2020-2021 and 2021-22. Five treatments including a control were designed for the experiment. Each treatment was replicated thrice. The treatments were:

$T_1$ = Ring Basin irrigation at 7 days interval with recommended fertilizer doses

$T_2$ = Fertigation at an alternate day with recommended fertilizer doses

$T_3$ = Fertigation at an alternate day with 20% less N and K than recommended doses

$T_4$ = Fertigation at an alternate day with 35% less N and K than recommended doses

$T_5$ = Fertigation at an alternate day with 50% less N and K than recommended doses

Each plot size was 4.0m × 4.0m. The soil was silty clay loam with an average bulk density of 1.5 gm/cc and field capacity of 28 percent (by weight basis). The experiment was laid out in a randomized complete block design. Seeds were shown on 14 November 2020 and 25 November 2021 to produce seedlings and these were transplanted in experimental plots on 09 December 2020 30 December, 2021. Fruits were harvested from 08 April 2020 and continued upto 13 April 2020 in the first year and 08 April in the 2nd year, respectively depending on maturity. The N and K in the form of urea and MP, respectively, were applied with irrigation water as per design of the treatments. The total P in the form of TSP, Gypsum, Borax Zn and Magnesium were applied as the basal dose in the pit. Cow-dung was applied at the rate of 10 kg/pit. Depleted soil moisture was applied to the soil in ring basin irrigation method (control). Soil moisture was determined before each irrigation by gravimetric method for control treatment. Irrigation was applied upto the field capacity of the soil.

A common irrigation of 14mm was applied from seedling to proper plant establishment. After one month of transplanting, every treatment was mulched by using paddy straw @2.0 t/ha. Sex feromen traps were placed in the field to control fruit fly infestation. Pruning was done continuously up to 8 to 10 nodes on the main branch. To control disease infection and insect infestation Otistin @20g/20L of water, Admire @4ml/15L of water and secure @30g/30L of water were sprayed. Weeding was done according to necessary.

The soil moisture was monitored in each plot by using the gravimetric method at 30 cm intervals down to 60 cm. The amount of applied water was measured by time-volume technique. Soil moisture was collected before sowing, before irrigation and after harvest. Irrigation water was applied by ring basin method to bring the soil moisture up to field capacity considering the effective root zone depth of 60cm. In case of drip irrigation, two drippers were installed per plant and dripper emission was assumed to be uniform. A 500L water tank was installed between two treatments and irrigated according to the design.

Seasonal water use (SWU) was calculated by adding applied water, effective rainfall (ER), and soil water contribution (SWC). Water productivity (WP) was calculated as the ratio of fruit yield and water use (SWU). Data on number of fresh and damaged fruit, number of fruit per plant, unit fruit weight, yield per plant and fruit yield was recorded. All the data were analyzed statistically by using R software and mean separation was done Duncan multiple range test at 5% level of significant. Financial analysis was also done with considering total operating cost, interest on operating cost, and land use cost.

In drip system, irrigation was applied at every alternate day meeting the demand of crop evapotranspiration. The average dripper discharge was 3.50 litres/hr. Experimental irrigation schedule was started just after plant establishment. In the early stage of crop, the irrigation time was 25 minutes in drip system and in fruiting stage, it was up to 60 minutes depending on crop ET. Data in respect of yield and yield contributing parameters viz. fruit weight, length, breadth, no. of fruits/plant and total yield were recorded.

***Fertigation system***

Four tank for four fertigation treatments ($T_2 - T_5$) were placed at a height of 1.0 m from the ground surface supported by bamboo structure on one side of the treatments. Each drum had a capacity of 215 litres of water. A water tap was attached to one side of the bottom part of each drum to which fertigation system was connected. The drippers were set according to the plant spacing in the treatments. Each plant received an emitter through which, water was applied to the plant in drips. A schematic diagram of the fertigation system is shown in Fig.1.

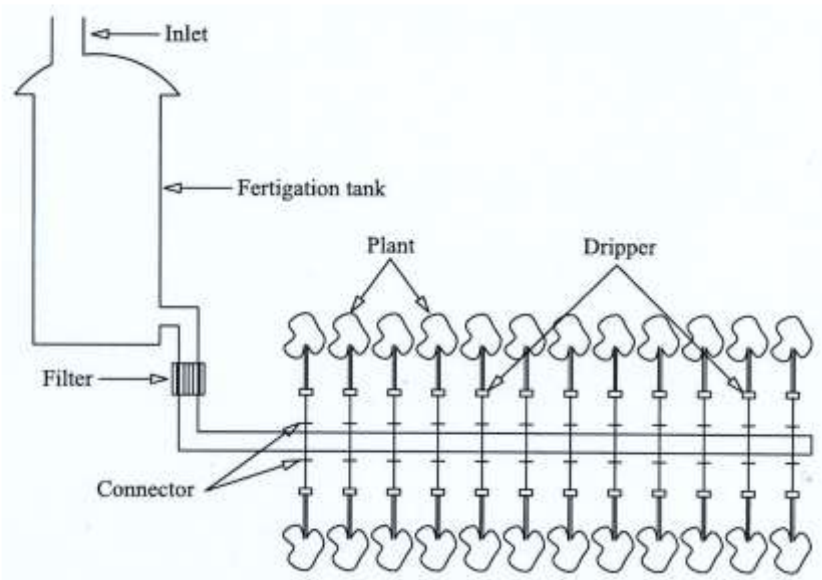


Fig.1 Schematic diagram of fertigation system.

## Results and Discussion

Fertigation effect on yield and yield contributing characters of bottle gourd were analyzed statistically and are presented in Table 1. The yield and yield contributing characters like no. of fruit/plant, yield per plot varied significantly. Referring to Table-1, the highest yield of 32.41 t/ha was obtained from treatment $T_4$ by applying 35% less N and K than recommended doses through drip system followed by treatment $T_5$ (30.71 t/ha) by applying 20% less N and K than recommended doses through drip system. But yield difference was not statistically significant. The highest yield obtained from$T_4$ was significantly differ with the yield obtained from ring basin method i.e. farmers practice. The lowest yield was found 24.09 t/ha by applying irrigation in ring basin method at 7 days interval with recommended fertilizer doses (farmer's practice). Irrigation water applied in different treatments was shown in Table 2. Referring to Table 2, it was seen that 413.64 mm water for ring basin method were needed during the season whereas only 166.33 mm water was needed in drip method. Water can be saved about 70% compared to ring basin method. There was no effective rainfall during the growing season 2020-21.

Table 1. Yield and yield contributing characters of pumpkin during 2020-21

| Treatment | Fruit length (cm) | Fruit dia (cm) | Fruits/ plant (no.) | Unit weight of fruit (kg) | Weight of fruits/plot (kg) | Yield (t/ha) |
|---|---|---|---|---|---|---|
| $T_1$ | 10.46 | 18.27 | 5.33 | 2.36 | 38.54 | 24.09 |
| $T_2$ | 11.13 | 18.07 | 5.67 | 2.42 | 46.56 | 29.09 |
| $T_3$ | 10.40 | 18.20 | 6.00 | 2.45 | 49.14 | 30.71 |
| $T_4$ | 11.50 | 18.87 | 5.50 | 2.59 | 51.85 | 32.41 |
| $T_5$ | 11.30 | 18.87 | 5.27 | 2.48 | 45.83 | 28.63 |
| CV (%) | 6.37 | 4.21 | 13.28 | 10.88 | 11.67 | 11.65 |
| $LSD_{0.05}$ | 1.31 | 1.46 | 1.38 | 0.50 | 10.19 | 6.36 |
| Tukey's HSD | 0.38 | 0.38 | 0.22 | 0.09 | 0.65 | 0.65 |
| P-value | 0.28 | 0.59 | 0.69 | 0.85 | 0.12 | 0.12 |

Table 2. Irrigation water applied in different treatments during 2020-21

| Treatment | Number of Irrigation applied | Dripper discharge (l/h) | Water for plant establishment (mm) | Irrigation water applied (mm) | Soil moisture contribution (mm) | Total water use (mm) | Water productivity ($kg/m^3$) |
|---|---|---|---|---|---|---|---|
| $T_1$ | 14 | 3.75 | 14 | 361 | 38.64 | 413.64 | 5.82 |
| $T_2$ | 25 | 3.75 | 14 | 192 | 35.33 | 241.33 | 17.49 |
| $T_3$ | 25 | 3.75 | 14 | 192 | 35.33 | 241.33 | 18.46 |
| $T_4$ | 25 | 3.75 | 14 | 192 | 35.33 | 241.33 | 19.48 |
| $T_5$ | 25 | 3.75 | 14 | 192 | 35.33 | 241.33 | 17.21 |

Economic analysis for fertigation over traditional system for pumpkin cultivation was done and is presented in Table 3. The economic analysis reveals that the benefit cost ratio is the highest of 2.60 was obtained from treatment $T_4$ by applying 35% less N and K than recommended doses through drip system followed by treatment $T_3$ (2.48) by applying 20% less N and K than recommended doses through drip system. The lowest BCR was found 1.88 by applying irrigation in ring basin method at 7 days interval with recommended fertilizer doses (farmer's practice). The higher return is also found (Tk. 29972.00) in fertigation ($T_4$) system by cultivating pumpkin from only 0.1 ha of land.

Table 3. Economic analysis for fertigation over traditional system for bottle gourd cultivation (for 1000 $m^2$ of land)

***(a). Fixed cost***

| Item | Quantity | Rate | Cost (Tk.) | | |
|---|---|---|---|---|---|
| | | | $T_1$ | Fertigation ($T_4$) | Fertigation ($T_3$) |
| Fertigation tank | 4 nos | 1000.00 | - | 4000.00 | 4000.00 |
| GI fittings and supporting platform | - | LS | - | 1000.00 | 1000.00 |
| 1.25 cm dia PVC pipe | 300 m | 4.00 | - | 1200.00 | 1200.00 |
| 0.32 m dia micro-tube | 750 m | 2.50 | - | 1875.00 | 1875.00 |
| **Total fixed cost, Tk.** | | | | **8075.00** | **8075.00** |

Expected life of the system = 4 years Fixed cost/year = 2018.00

***(b). Variable cost***

| Item | Cost (Tk.) | | |
|---|---|---|---|
| | Ring basin ($T_1$) | Fertigation ($T_4$) | Fertigation ($T_3$) |
| Seedlings | 160.00 | 160.00 | 160.00 |
| Pit making | 250.00 | 250.00 | 250.00 |
| Fertilizer | 1915.00 | 1600.00 | 1525.00 |
| Trail | 12500.00 | 12500.00 | 12500.00 |
| Irrigation cost | 2000.00 | 500.00 | 500.00 |
| Labour | 2400.00 | 1600.00 | 1600.00 |
| **Total variable cost, Tk.** | **19225.00** | **16610.00** | **16535.00** |

***(c). Return***

| Item | Return, Tk. | | |
|---|---|---|---|
| | Ring basin ($T_1$) | Fertigation ($T_4$) | Fertigation ($T_3$) |
| Yield/1000$m^2$ (metric ton) | 2.41 | 3.24 | 3.07 |
| Selling rate (Tk./ton) | 15000.00 | 15000.00 | 15000.00 |
| Gross return (Tk.) | 36150.00 | 48600.00 | 46050.00 |
| Total fixed cost/year (Tk.) | - | 2018.00 | 2018.00 |
| Total cost/year (Tk.) | 19225.00 | 18628.00 | 18553 |
| Net return (Tk./ha) | 16925.00 | 29972.00 | 27497.00 |
| **Benefit cost ratio (BCR)** | **1.88** | **2.60** | **2.48** |

Yield and yield contributing characters of pumpkin during 2021-22 were analysed and shown in table 4. This year a large no. of fruit was damaged due to insect and pest damage. So, the yield is comparatively low compared to first year. The experiment will be continued for the next year.

Table 4. Yield and yield contributing characters of pumpkin during 2021-22

| Treatment | Fruit length (cm) | Fruit dia (cm) | Fruits/ plant (no.) | Unit weight of fruit (kg) | Weight of fruits/plot (kg) | Yield (t/ha) |
|---|---|---|---|---|---|---|
| $T_1$ | 11.40 | 14.51 | 1.25 | 1.91 | 9.57 | 5.98 |
| $T_2$ | 12.67 | 17.40 | 1.33 | 2.29 | 12.29 | 5.68 |
| $T_3$ | 12.27 | 18.20 | 2.58 | 2.28 | 21.55 | 13.47 |
| $T_4$ | 11.93 | 17.87 | 3.17 | .15 | 23.38 | 14.61 |
| $T_5$ | 13.00 | 18.33 | 3.33 | 2.31 | 25.72 | 16.07 |
| CV (%) | 5.06 | 7.51 | 3.33 | 7.71 | 13.24 | 12.66 |
| $LSD_{0.05}$ | 1.17 | 2.44 | 1.33 | 0.73 | 8.09 | 4.76 |

## Conclusion

The highest yield of pumpkin 32.41 t/ha was obtained from treatment $T_4$ by applying 35% less N and K than recommended doses through drip system followed by treatment $T_3$ (30.71 t/ha) by applying 20% less N and K than recommended doses through drip system. This is the first year result. During the second year a large number of first was damaged due to inset and pest damage. To, the experiment should be continued for the next year.

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# EFFECT OF IRRIGATION ON MANGO FRUIT CRACKING IN CHATTOGRAM REGION

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## Abstract

The study was conducted at existing HRC Mango Orchard of Regional Agricultural Research Station, Hathazari, Chattogram during the Rabi season of 2019-20, 2020-21 and 2021-22 to explore the optimal period of irrigation to mitigate mango fruit cracking. Five treatments were applied: $T_1$ (rain-fed i.e. local practice), $T_2$ (irrigation at full bloom), $T_3$ (irrigation at fruiting setting), $T_4$ (irrigation at full bloom and fruit setting), and $T_5$ (irrigation at 2 weeks interval),). The highest yield (76.5Kg plant$^{-1}$, 74.6 Kg plant$^{-1}$ and 74.8 Kg plant$^{-1}$ in successive years) was found at higher frequency irrigation ($T_5$). The maximum irrigation (average 1865 litres plant$^{-1}$) was applied at two weeks interval irrigation ($T_5$). In rain-fed condition ($T_1$), yield was lowest (56.8 Kg plant$^{-1}$ and 55.2 Kg plant$^{-1}$ and 43.5 Kg plant$^{-1}$ in successive years). The lowest number of fruits dropping (average 18 no. fruits) was occurred in irrigation at full bloom and fruit setting ($T_4$). The lowest number of cracking (average 14no.fruits) as well as the highest sweetness (average TSS=24%) occurred irrigation at fruit setting ($T_3$) and the benefit-cost ratio was also higher in this treatment.

## Introduction

Mango (*Mangifera indica*) is one of the most popular fruits in Bangladesh. Mango belongs to the familyAnacardiaceae is a tropical to sub-tropical fruit, originated in the Indian sub-continent (Indo-Burma region)in the prehistoric times. Bangladesh is the world's eighth largest mango producing country as it produces about 1,047,850 tons of mangos every year which accounts for 3.9 percent of the world total mango production.

Mango production increases day by day in Chattogram region e.g. 71459 M.ton.in 2015 and 81112 M.ton in 2016 (BBS, 2017). Irrigation is one of parameters besides nutrition management that increases the yields and improves the quality of mango (W. Spreer et al., 2007). In this region, farmers are still empirically applying water based upon experiences, without technical criteria. As a result, chances are that the mango crop cannot uptake enough water for its development and production due to soil water stress or excess. This kind of irrigation management may also lead to an increase in production costs due to excess amount of water applied that affects the sustainability of water resources. Therefore irrigation management for the mango crop should follow technical criteria, so that water is applied at the right time and at the right amount.

Alam et al. (2017) found that the fruits dropping and cracking of mangoes causes four reasons-diseases, insects, nutrient deficiency, water scarcity in Bangladesh. Mango fruit cracking occurs in Chattogram region during dry season (Nov-March). The cracked fruits lose keeping quality and unsuitable for transportation and consumption. The scarcity of soil moisture and also excess of soil moisture cause fruit cracking (Saran et al., 2008). There is also water scarcity during this period in Chattogram region. So, Optimal stages of irrigation in mango production may save water and boost up quantity and quality (fruit cracking) of mango. The aim of this experiment is to find out the critical stage of irrigation to mitigate mango fruit cracking of mango.

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## Materials and Methods

A field experiment was conducted at existing HRC Mango Orchard (BARI Aam-4, Age 5-7 years), Hathazari, Chattogram (Figure 1) during the rabi season (from November to June) of 2019-20 as well as 2020-21and also 2021-22. The design of a randomized complete block was performed with three replication and five treatments.The five irrigation treatments are:

1) Rain fed condition i.e. Local practice ($T_1$)
2) Irrigation at full bloom ($T_2$)
3) Irrigation at fruit setting ($T_3$),
4) Irrigation at full bloom and fruit setting ($T_4$)
5) Irrigation at 2 weeks intervals ($T_5$)

Fertilizer dose and methods of application were Manure (35 kg/plant), Uea (875 gm/plant), TSP (437 gm/plant), MOP (350 gm/plant), Zn (350 gm/plant), Zn-SO4 (17 gm/plant), and Boric acid (35 gm /plant) (FRG, 2012).

Amount of water to be applied, during each irrigation event, was estimated by measuring soil moisture depletion from the field capacity. The water was applied by hose pipe with ring basin method.

Water content was calculated gravimetrically or volumetrically. Gravimetric soil water content is the mass ofwater divided by the mass of dry soil. It was measuredby weighing a mass of wet soil, drying the soil for 24 hours at 105 $^{0}$C in Oven, and then reweighing the sample(Waller & Yitayew, 2016).

$$\Theta_{grav}\ (gm/gm) = \frac{Mass\ of\ water(gm)}{Mass\ of\ dry\ soil\ (gm)} = \frac{Mass\ of\ wet\ soil\ (gm) - Mass\ of\ dry\ soil\ (gm)}{Mass\ of\ dry\ soil} \quad (1)$$

$$\Theta_{v}\ (cm^3/cm^3) = \theta_{grav} \times soil\ bulk\ density\ (gm/cm^3) \quad (2)$$

The depth of irrigation water requirement was estimated with the guideline of Michael (2007) as follows in equation (3).

$$d_{IR} = \frac{(FC - RL) \times A_s \times D}{100} \quad (3)$$

where, $d_{IR}$ = depth of irrigation water requirement (mm), FC= field capacity (%) which measured byponding water method on the soil surface (Michael, 2007), RL= residual moisture content (%) which measured before irrigation gravimetrically, $A_s$ = apparent specific gravity of soil, D= depth of effective root zone to be irrigated (mm).

The time, required to be irrigation, was calculated following equation (4).

$$t = \frac{d_{IR} \times A}{Q \times 1000} \quad (4)$$

where t = time to be irrigated (min), $d_{IR}$ = depth of irrigation water requirement, A = area of plot ($m^2$), Q= discharge ($m^3$/min).

The data were analyzed with "agricolae" R version 4.0.0 software package (Mendiburu, 2020).

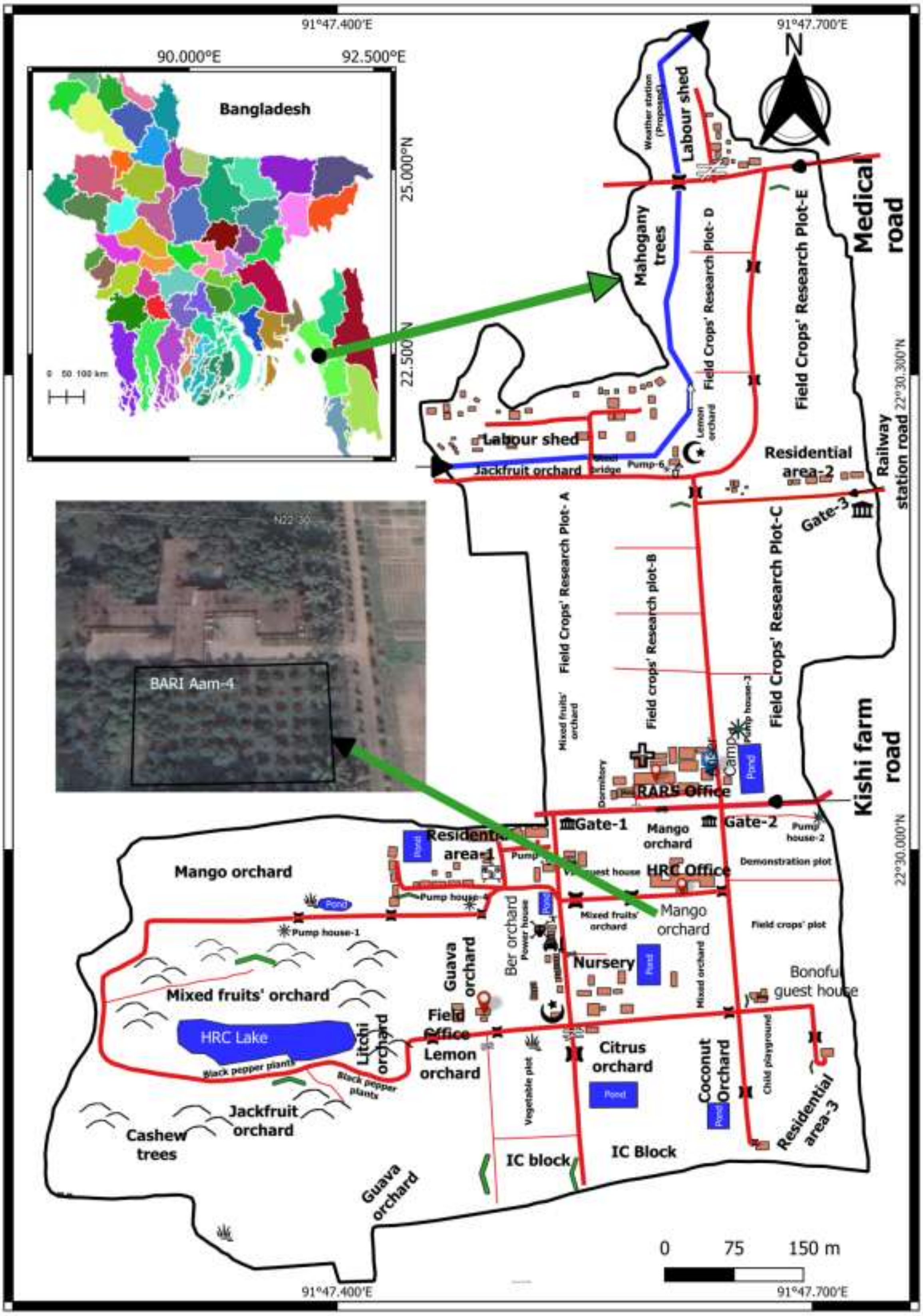


Figure 1: Map of this experiment site

## Results and Discussion

The highest yield (76.5Kg plant$^{-1}$, 74.6Kg plant$^{-1}$ and 74.86Kg plant$^{-1}$ in first, second and third years) was obtained at two weeks interval irrigation ($T_5$) and the lowest yield (56.8 Kg plant$^{-1}$ and

55.2Kg plant$^{-1}$ 43.5 Kg plant$^{-1}$ in first, second and third years) was in rainfed condition ($T_1$). The fruit weight per plant was also highest (average 516.0 gm/plant) and lowest (average 340.3 gm plant$^{-1}$) in irrigation at two weeks interval and rainfed condition respectively. The more frequent irrigation was more response to yield. One irrigation event occurred at both full bloom and fruit setting. The fruiting stage irrigation was responsive to yield which was more yield than full bloom irrigation (Table 1 and Table 2).

The fruits' cracking at two weeks interval irrigation ($T_5$**)** was also the highest level (39, 37 and 32.3 no. fruits in successive years) than any other treatments. The lowest number of fruits cracking (15, 13 and 13.3 no.Fruits in successive years) was occurred at fruit setting irrigation. The results revealed that the less irrigation and excessive irrigation than a certain level may cause more fruit cracking which was similar findings to Saran et al.(2008) .However, this study was found that irrigation at fruiting stage was more critical stage of irrigation.

The highest number of fruits' dropping (average 33 no. Fruits in three years) was obtained at rainfed condition ($T_1$) which was control treatment in comparison to other treatments. The lowest number of fruit dropping (average 18 no. Fruits in successive years) was occurred in irrigation at full bloom plus fruit setting stage ($T_4$). So, irrigation at both full bloom and fruit setting stage were crucial for reduction of fruits dropping. Spreer et al.(2009) also had evidence that fruits dropping without irrigation were higher.

The percentage of TSS at rainfed condition ($T_1$) was less than irrigation at fruit seting ($T_3$). The sweetness (TSS) was the lowest (average 21%) in two weeks interval irrigation ($T_5$) and the highest sweetness (24%) was at fruit setting-irrigation ($T_3$).Therefore, the more frequent interval irrigation decreased the sweetness of mango. Léchaudel et al. (2005) also showed that the frequent irrigation water supply reduced the sugar or sweetness of mango. This study revealed that irrigation at fruit setting ($T_3$) was the optimal stage of irrigation to maintain the level of higher sweetness.

Irrigation at two weeks interval was required more water (average 1865 liters/plant) than any other irrigation treatments (Table 2). The cost and benefit of this irrigation treatment ($T_5$) was higher although the benefit-cost ratio was lowest (average BCR=1.5). The benefit-cost ratio of irrigation at fruit setting was highest (average BCR about to 3). Rahman et al. (2019) also found that the benefit-cost ratio of mango production at farmer's level in Bangladesh was 3.00.

However, with respect to economic return and fruits cracking, the irrigation at fruit setting was the more beneficial and suitable stage of irrigation ($T_3$).

Table 1 Irrigation effect on Mango production

| **2019-2020** | | | | | | |
|---|---|---|---|---|---|---|
| Treatment | No of fruits per plant | Weight per fruit (gm) | Yield per plant (kg) | No of fruits drop | No of fruit cracks | TSS (%) |
| $T_1$ | 160.0 | 355.0 | 56.8 | 38.3 | 32.7 | 23.0 |
| $T_2$ | 142.3 | 410.0 | 58.4 | 37.7 | 25.7 | 22.3 |
| $T_3$ | 147.0 | 458.3 | 67.4 | 24.7 | 15.0 | 24.0 |
| $T_4$ | 145.7 | 485.0 | 70.6 | 21.0 | 25.0 | 21.7 |
| $T_5$ | 145.3 | 526.7 | 76.5 | 31.0 | 39.0 | 19.3 |
| CV (%) | 3.8 | 2.8 | 4.3 | 10.8 | 11.6 | 4.3 |
| LSD (5%) | 10.7 | 23.8 | 5.4 | 6.2 | 6.0 | 1.8 |
| **2020-2021** | | | | | | |
| $T_1$ | 165.0 | 335.0 | 55.2 | 33.3 | 30.3 | 23.1 |
| $T_2$ | 145.7 | 440.0 | 64.2 | 32.7 | 23.7 | 22.5 |

| | | | | | | |
|---|---|---|---|---|---|---|
| $T_3$ | 148.0 | 456.7 | 67.6 | 19.7 | 13.0 | 24.0 |
| $T_4$ | 146.3 | 489.0 | 71.6 | 16.0 | 23.0 | 21.2 |
| $T_5$ | 145.7 | 511.7 | 74.6 | 26.0 | 37.0 | 22.0 |
| CV (%) | 4.3 | 4.8 | 6.9 | 12.8 | 12.7 | 5.7 |
| LSD (5%) | 12.2 | 40.6 | 8.7 | 6.2 | 6.0 | 2.4 |
| **2021-22** | | | | | | |
| $T_1$ | 131.3 | 509.7 | 43.5 | 28.3 | 26.3 | 23 |
| $T_2$ | 142 | 479 | 62.1 | 27.7 | 22.3 | 22.3 |
| $T_3$ | 150 | 450 | 67.5 | 14.7 | 13.3 | 24 |
| $T_4$ | 152 | 437.7 | 72.8 | 17.3 | 23 | 21.7 |
| $T_5$ | 146.7 | 331 | 74.8 | 29 | 32.3 | 22 |
| CV (%) | 1.9 | 4.9 | 4.9 | 15.3 | 9.8 | 5.8 |
| LSD (5%) | 5.1 | 39.7 | 5.9 | 6.7 | 4.3 | 2.5 |
| **Combined analysis of three seasons (from 2019 to 2022)** | | | | | | |
| T1 | 152.1 | 340.3 | 51.8 | 33.3 | 29.8 | 23.0 |
| T2 | 143.3 | 429.2 | 61.6 | 32.7 | 23.9 | 22.3 |
| T3 | 148.3 | 455.0 | 67.5 | 19.7 | 13.8 | 24.0 |
| T4 | 148.0 | 484.3 | 71.7 | 18.1 | 23.7 | 21.7 |
| T5 | 145.9 | 516.0 | 75.3 | 28.7 | 36.1 | 21.1 |
| CV (%) | 3.5 | 4.2 | 5.5 | 12.8 | 11.5 | 5.3 |
| LSD (5%) | 5.1 | 18.4 | 3.5 | 3.3 | 2.9 | 1.2 |
| ***Note:*** *$T_1$=Rain fed , $T_5$= Irrigation at 2 weeks interval, $T_2$= Irrigation at full bloom, $T_3$= Irrigation at fruit setting, $T_4$= Irrigation at full bloom and fruit setting* | | | | | | |

Table 2 Irrigation event, amount of irrigation, and Profitability analysis of mango production

| **2019-2020** | | | | | | | |
|---|---|---|---|---|---|---|---|
| Treatment | Irrigation no. | Amount of irrigation (Liters/plant) | Effective rainfall (Liters/m2) | Yield per plant (Kg) | Benefit (Tk/plant) | Cost (Tk/plant) | Benefit -Cost Ratio |
| $T_1$ | 0 | 0 | 28.7 | 56.8 | 2272 | 780 | 2.91 |
| $T_2$ | 1 | 1000 | 28.7 | 58.4 | 2336 | 900 | 2.60 |
| $T_3$ | 1 | 1200 | 28.7 | 67.4 | 2696 | 900 | 3.00 |
| $T_4$ | 2 | 1300 | 28.7 | 70.6 | 2824 | 1300 | 2.17 |
| $T_5$ | 10 | 2000 | 28.7 | 76.5 | 3048 | 2000 | 1.52 |
| **2020-2021** | | | | | | | |
| $T_1$ | 0 | 0 | 50.2 | 55.2 | 2210 | 800 | 2.8 |
| $T_2$ | 1 | 950 | 50.2 | 64.2 | 2568 | 950 | 2.7 |
| $T_3$ | 1 | 1130 | 50.2 | 67.6 | 2702 | 950 | 2.8 |
| $T_4$ | 2 | 1270 | 50.2 | 71.6 | 2862 | 1400 | 2.0 |
| $T_5$ | 10 | 1852 | 50.2 | 74.6 | 2982 | 2200 | 1.4 |
| **2021-22** | | | | | | | |
| $T_1$ | 0 | 0 | 87.0 | 43.5 | 1740 | 850 | 2.05 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| $T_2$ | 1 | 700 | 87.0 | 62.1 | 2484 | 970 | 2.56 |
| $T_3$ | 1 | 1010 | 87.0 | 67.5 | 2700 | 970 | 2.78 |
| $T_4$ | 2 | 1108 | 87.0 | 72.8 | 2912 | 1250 | 2.33 |
| $T_5$ | 10 | 1743 | 87.0 | 74.8 | 2992 | 1900 | 1.57 |
| **Mean of three seasons (from 2019 to 2022)** | | | | | | | |
| $T_1$ | 0 | 0 | 55.3 | 56.04 | 1990.75 | 810.0 | 2.44 |
| $T_2$ | 1 | 883.3 | 55.3 | 61.29 | 2467.8 | 940.0 | 2.61 |
| $T_3$ | 1 | 1113 | 55.3 | 67.47 | 2699.4 | 940.0 | 2.85 |
| $T_4$ | 2 | 1226 | 55.3 | 71.10 | 2878.08 | 1316.7 | 2.22 |
| $T_5$ | 10 | 1865 | 55.3 | 75.53 | 3006.65 | 2033.3 | 1.51 |

***Note:*** *$T_1$=Rain fed, $T_5$= Irrigation at 2 weeks interval, $T_2$= Irrigation at full bloom, $T_3$= Irrigation at fruit setting, $T_4$= Irrigation at full bloom and fruit setting. Assume labor per day Tk550 and selling price per Kg at farm gate Tk40.*

## Conclusion

From the previous three year experiment, Irrigation at fruit setting of mango ($T_3$) was the more profitable, sweetness, and lower fruits cracking although its yield was lower than the highest frequency irrigation ($T_5$) at two weeks intervals.

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# YIELD AND WATER PRODUCTIVITY INDICES OF DIFFERENT ONION VARIETIES UNDER SPRINKLER IRRIGATION

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## Abstract

*To evaluate the performance of four onion varieties under sprinkler irrigation and their sensitivity to water stress, a study was conducted at the experimental field of IWM Division, BARI during the winter season of 2020 – 2021 and 2021 – 2022. The experiment comprised of five irrigation treatments with sprinkler system based on 60%, 80%, 100%, 120% and 140% of crop water use (ETo) laid out in split-plot design with three replications. Irrigation water was applied at a fixed 6-day interval with sprinkler system throughout the crops growing season. Onion sensitivity to water stress was determined using a yield response factor (Ky) that derived from the linear relationship between relative evapotranspiration deficits (1-ETa/ETm) and relative yield decrease (1-Ya/Ym). Statistical analysis revealed that leaf number was not much affected by the level of irrigation while, plant height, bulb diameter, bulb unit weight and total bulb yield was affected significantly (P<0.05) by the irrigation regimes. Among the four onion varieties, the highest plant height, bulb diameter and unit bulb weight contributed to the highest yield of 31.02 t/ha and 31.56 t/ha in first and second year, respectively, for BARI Piaj-4 ($V_4$) under140% ETo water regime while the lowest yield of 11.74 and 14.01 t/ha was obtained from BARI Piaj-1 (V1) under 60%ETo water regime. For varieties, $V_1$ and $V_3$, highest yields were obtained under 120% ETo water regime while the same were obtained under 140% ETo water regime for $V_2$ and $V_4$. On average over the years, bulb yields of V2, V3 and V4 varieties were comparable and significantly higher than the yield of V1 under all irrigation regimes. Value of Ky determined for the whole growing season over the study years was found higher for $V_4$ (Ky: 1.13),V2 (1.12) and $V_3$ (Ky: 1.05) than BARI Piaj-1 (Ky: 0.913) indicates that the varieties $V_4$, $V_3$ and $V_2$ are more sensitive to water stress. This fact is also evident by the water productivity (WP) with higher value obtained under higher water regimes (100 - 120% ETo) in case of $V_4$, $V_3$, and $V_2$ but for $V_1$, higher WP was obtained from 80 - 100% ETo water regime. Though seasonal evapotranspiration was higher under wetter water regimes, yield was somewhat lower and consequently WP was the lowest. Considering Ky as a limiting factor, application of irrigation at 80 - 100% ETo was a marginal for $V_1$ and $V_2$ and 100 - 120% ETo for $V_2$, $V_3$ and $V_4$, beyond that yield losses are unacceptable.*

## Introduction

Onion is considered as one of the most important spice and vegetable crop grown in Bangladesh. It is grown extensively during winter season in Bangladesh, occupying the second position both in area and production (BBS, 2013) next to chilli. Though it is grown more or less in all the districts of the country, the dominant areas are the greater districts of Faridpur, Rajshahi, Jessore, Pabna and Kushtia. Land area under onion cultivation in Bangladesh was 0.33 million ha during 2000 - 2001 and within a span of 12 years, it has increased four- fold to 1.32 million ha (BBS, 2013). However, the bulb yield of onion (8.6 t $ha^{-1}$) in Bangladesh is less than many other onion producing countries. It is about half of the world average (17 t $ha^{-1}$) and four fold lower than those achieved in the European Union (30-35 t $ha^{-1}$) (FAOSTAT 2010). On an average, the total annual

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requirement of onion in Bangladesh stands at 2200 thousand metric tons whereas the total production is about 1168 thousand metric tons and thereby, there is a shortage of 1030 thousand metric tons per annum. To meet this shortage, Bangladesh has to import onion every year at the cost of its hard earned foreign currency. The reasons for the lower productivity of onion in Bangladesh are many including inadequate management practices, short day length during the growing season, low organic carbon content of the soil, shorter (3–4 months) growing period, as well as poor water management. However, to increase the productivity, the grower must have prior knowledge of the crop yield responses to deficit irrigation. Many investigations have been carried out worldwide regarding the effects of deficit irrigation on yield of mainly horticultural crops (Olalla et al. 2004; Bazza and Tayaa, 1999; Faberio et al. 2003 and Sezen et al. 2008). Other experiments with onion (Bekle et al., 2007) showed that deficit irrigation throughout the growing season of onion as 50 and 75% of ETc reduced yields from full irrigation and resulted in the highest water saving and crop water use efficiency. Kumar et al. (2007) also investigated the impact of deficit irrigation strategies on onion yield and water savings. They reported that applying 80 and 60% of crop water requirements resulted in yield decreases of 14 and 38% and saved 18 and 33% of irrigation water compared to full irrigation, respectively.

The evaluation of stress associated with the yield due to soil water deficit during the crop growing season can be obtained by the estimation of the yield response factor (Ky) that represents the relationship between a relative yield decrease (1–Ya/Ym) and a relative evaporation deficit (1–ETa/ETm). Determination of Ky values after adaptive research has been carried out in numerous studies for various crops and under different environments. Results showed a wide range of variations in Ky values and suggest that the within-crop variation in Ky may be as large as that between crops (Stanhill et al., 1985). Moreover, factors other than water such as nutrients, different cultivars, ETo. also affect the response to water. Vaux and Pruitt (1983) suggest that it is highly important to know not only the Ky values from the literature but also those determined for a particular crop species under specific climatic and soil conditions. In fact, adjustments for site-specific conditions would be needed if greater accuracy is sought This is because Ky may be affected by other factors besides soil water deficiency, viz. soil properties, climate, growing season length and growing technology. Water deficit effect on crops yield can be presented in two ways, for individual growth periods or for the total growing season. Kobossi and Kaveh (2010) suggested Ky values for the total growing period instead for individual growth stages as the decrease in yield due to water stress during specific periods, such as vegetative and ripening periods, is relatively small compared with the yield formation period, which is relatively large.

Both variety and water management practices play a major role in increasing the productivity of crops. The crops having higher yield potential and higher yield response to water have a wide range of water productivity. Onion crop needs adequate management practices especially proper irrigation management to contribute potential yield. The principle and pervasive reasons of low productivity of onion in our country is due to lack of high yielding varieties and proper irrigation management practices. Improved variety contributes substantially to enhance crop yield (Shaikh *et. al.,* 2002). Recently, some private seed companies have released few high yielding winter onion varieties and those are cultivating by farmers with same irrigation practices they follow for BARI onion-1. As water management may vary with the crop varieties and their yield response to water, so farmers are not getting good harvest as expected. However, to increase the productivity, the grower must have prior knowledge of the crop yield responses to deficit irrigation. Hence, it is warranted to test the water requirement of the commercial varieties and its yield potential compared to BARI Piaj -1. Therefore, the objective of this study was to find out the proper irrigation scheduling of commercial onion varieties and their yield response to water compared to local variety.

## Materials and Methods

The field experiment was conducted during the winter season of 2020 – 2021 and 2021 – 2022, between the months of December and March, at the research field of Irrigation and Water Management Division, Bangladesh Agricultural Research Institute (BARI) (Latitude 24.00$^{o}$ N, Longitude 90.25$^{o}$E and altitude 8.40 m msl), Gazipur. The average temperature, relative humidity, wind speed and pan evaporation rate during the crop growing season ranged from 14.5 to 26.4 $^{0}$C, 56–89%, 0.76–10.87 km $h^{-1}$ and 1.6–3.5 mm $d^{-1}$, respectively. Total rainfall occurred during crop growing season was recorded as only 2 mm in first season and 36 mm in the second season and the total was considered effective. The percentage of sand, silt and clay in the experimental soil were 36.5, 35.4 and 28.1, respectively. Field capacity, wilting point and bulk density of top 30 cm of the soil were 28.5%, 13.72% and 1.46 g $cm^{-3}$. The concentrations (kg $ha^{-1}$) of N, $P_2O_5$and $K_2O$ were 51.1, 12.5 and 265.6, respectively. The soil had an organic matter content of 1.04%.

The experiment was set up in a split-plot design with three onion varieties and five different irrigation treatments that were replicated thrice. Sprinkler irrigation with five different water levels were applied compensating crop coefficient (Kc) and potential evapotranspiration (ETo) based predicted evapotranspiration loss (ETo). Each of the onion varieties experienced five levels of sprinkler irrigation as follows:

Onion varieties

$V_1$= BARI Piaj-1
$V_2$= Hybrid (Lal Teer))
$V_3$= Taherpuri King (Lal Teer)
$V_4$= BARI Piaj-4

Irrigation levels

$I_1$= Sprinkler irrigation at 60% ETo
$I_2$= Sprinkler irrigation at 80% ETo
$I_3$= Sprinkler irrigation at 100% ETo
$I_4$= Sprinkler irrigation at 120% ETo
$I_5$= Sprinkler irrigation at 140% ETo

Onion varieties were kept in the main plots and irrigation levels in the sub-plots. The treatments with the same irrigation regime were arranged in a line covering all four varieties for better management of irrigation. Since, the characteristics of the experimental land were homogeneous, there was little possibility of variation in results for such arrangements of the treatments. Each plot was of 4 m × 3.75 m size surrounded by 1.5 m wide buffer strip to restrict lateral seepage of water in-between adjoining plots. Forty days old seedlings of onions (cv. BARI Piaz- 1, Taherpuri Super, Taherpuri King and BARI Piaj-4)) were planted at 15 cm × 10 cm spacing on 30 December 2020 and 27 December 2021. During land preparation, farm yard manure @ 5 t/ha was properly mixed with the soil. Fertilizers were applied @ 115 kg N, 60 kg P and 60 kg K per hectare. Half of the nitrogen and potassium and the full dose of phosphorus were applied at planting and the rest half of the nitrogen and potassium was applied in two equal splits at 25 and 50 days after planting.

Just after transplanting, a common irrigation was applied to all plots for establishing the plants. Thereafter, irrigation treatments started at 12 DAT and subsequent applications were applied according to the treatments design. Irrigation was applied through sprinkler system based on reference evapotranspiration (ETo). Reference evapotranspiration (ETo) was calculated on a daily basis from daily meteorological data by Penman–Monteith's equation using CROPWAT computer programme. Daily meteorological data required for CROPWAT model including maximum and minimum air temperature, relative humidity, wind speed at 2 m height and sun shine hour were collected from a weather station about 1.0 km away from the study site. The daily irrigation requirement for the crop was calculated by subtracting the effective rainfall from the computed ETo. Time of operation of sprinkler system was calculated for different levels of irrigation dividing water requirement of the crop over irrigation intervals (6 d) by discharge of a sprinkler nozzle. The duration of operation was controlled with gate valves provided at the inlet of each lateral. Soil water content measurements were made from 0-15, 15-30 and 30-45 cm depths before and after each irrigation as well as at transplanting and at harvest and after each rainfall event by gravimetric method. Seasonal crop water use (SET) was estimated using the water balance method (Walker and Skogerboe, 1987) as:

$$SET = I + P - D - R \pm \Delta SWS \quad ..............................(1)$$

Where P is precipitation (mm), I is irrigation (mm), D is the drainage (mm), R the run-off and ΔSWS is the variation in water content of the soil profile. The change in soil water contents at 30–45 cm soil layer was considered to be deep percolation. Run-off was taken to be zero since it did not occur with the use of micro-sprinkler irrigation system.

The recommended plant protection measures were adopted as and when required. Irrigation was stopped 15 days before harvesting in all treatments. Ten plants from each plot were selected randomly and tagged for recording growth parameters viz., plant height, number of leaves and neck girth at 70 DAT. Leaf area and above ground dry matter were also recorded on 10 plants at different phenological stages. Yield parameters viz., bulb diameter, bulb length, bulb unit weight were recorded from the plants used for recording observations. The bulbs were harvested at full maturity stage on 27 March 2021 and 26 march 2022. Yield of onions were measured after naturally drying the bulbs for seven days. The bulb yield per hectare was calculated based on the plot yield.

The yield response factor (Ky) of onion was estimated using the following relationship given by Doorenbos and Kassam (1979).

$$\left(1-\frac{Ya}{Ym}\right) = Ky\left(1-\frac{ETa}{ETm}\right) \quad ...........................(2)$$

Where,

Ya = the actual harvested yield (kg $ha^{-1}$),
Ym = the maximum harvested yield (kg $ha^{-1}$),
Ky = the yield response factor,
ETa = the actual evapotranspiration (mm) corresponding to Ya,
ETm = the maximum evapotranspiration (mm) corresponding to Ym,
(1–ETa/ETm) = the relative evapotranspiration deficit, and
(1–Ya/Ym) = the relative yield decrease

The data collected during the experimental period were subjected to statistical analysis using MSTAT computer program to interpret the results. Whenever treatment effects were significant, least Significance Differences (LSD) test was done using analysis of variance technique as described by Gomez and Gomez (1984).

## Results and Discussion

### Plant height

The height of onion plant was not much affected by the variety, but significantly by the irrigation regimes (Table 1a and 1b). In general, application of water with higher regime produced taller plant, but it was insignificant compared to lower water regime. The plant height, on average, ranged from 51.60 to 63.94 cm in the first year and 52.28 to 60.52 in the second year, with the shortest and tallest plant height was observed from treatment receiving 60% and 120% or 140% ETo, respectively. However, variety $V_2$ and $V_3$ produced the taller plant than the varieties $V_1$ and $V_4$, with $V_1$ had the shortest height and $V_3$ the tallest. Variation in plant height with the changing in irrigation regimes was found greater in the variety $V_3$ and $V_4$ than other two varieties. It ranged from 53.87 to 66.40 cm and 50.60 to 61.47 cm for $V_4$, 53.13 to 66.10 cm and 53.93 to 63.07 cm for $V_3$, 52.07 to 64.73 cm and 54.87 to 61.13 cm for $V_2$ and from 47.33 to 59.07 and 49.73 to 58.27 mm for $V_1$ in the first and second year, respectively, with the lowest value for 60% and the highest value for 140% ETo, except for $V_1$ in the first year and V2 in the second year, where highest plant height obtained from 120%ETo water regime. The increasing of plant height with adequate soil moisture application is related to water in maintaining the turgid pressure of the plant cells which is the main reason for the growth (Fabeiro et al., 2002). On the contrary the shortening of plant height under soil moisture stress may be associated with the closure of stomata to reduce crop evapotranspiration, which leads to reduce uptake of $CO_2$ and nutrient. Therefore, photosynthesis and other biochemical reactions are hindered that eventually affecting plant growth. This finding is in line with the result that has been obtained by Fabeiro et al., 2003, indicated that soil water supply is directly proportional with plant height growth.

### Leaf number

The number of leaves per plant ranged from 6.79 to 7.98 in the first year and 6.57 to 7.77 in the second year, with minimum in 60% ETo and maximum in 140% ETo water regime across the varieties. Among the varieties, $V_2$ had the highest leaf number closely followed by $V_4$ and $V_3$ while $V_1$ had the lowest number of leaves per plant. With the increasing in irrigation regime from 60% to 140% ETo, the leaf number increased from 6.70 to 7.58 for $V_1$, 6.92 to 8.13 for $V_2$, 6.87 to 8.17 for $V_3$ and from 6.67 to 8.04 for $V_4$ in the first year (Table 1) and from 6.60 to 7.67 cm, 6.13 to 7.60 cm, 6.87 to 8.00 cm and from 6.53 to 7.30 cm for $V_1$, $V_2$, $V_3$ and $V_4$, respectively (Table 1b). In case of $V_1$, $V_3$ and $V_4$, leaf number showed no significant differences due to variation in water regimes. But variation in water regimes made significant differences ($p<0.05$) in leaf numbers for $V_2$ varieties. Treatment receiving 60% ETo had significantly lower number of leaves than treatment receiving 140% ETo. Over the varieties, number of leaves gradually increased with the increased in water regime from 60%ETo to 140%ETo. The highest number of leaves at 140% ETo with corresponding values being 7.58, 8.13, 8.17 and 8.04 in the first year and 7.67, 7.60, 8.00 and 7.60 in the second year, respectively, for V1, V2, V3 and V4. Treatment receiving 60% ETo had significantly lower number of leaves than treatment receiving 120-140% ETc. Number of leaves per plant under 80% and 100% Eto water regimes were identical. Similarly, no significant difference was observed in leaves number between 120% ETo and 140% ETo water regimes. Similar increments in leaf number with the increase of irrigation regimes have earlier been reported by Wakchaure et al. 2018.

**Bulb length and diameter**

The application of deficit irrigation affected the size of onion bulb. The highest bulb length and diameter was recorded from the wettest treatment 120-140% ETo non-significantly followed by 100% ETo. The least bulb length and diameter was recorded from treatment receiving 60% ETo and this was significantly different to treatment receiving higher irrigation regimes. In general, bulb diameter was greater than bulb length for all varieties studied, except variety $V_4$. Bulb length and diameter of the variety $V_1$ and $V_2$ were identical and significantly lower than variety $V_3$ and $V_4$. Like the bulb size, unit bulb weight was found higher for wetter treatments than for drier treatments. Variety $V_4$ produced the bigger size bulbs with higher unit weight (56.10 g and 63.29 g in the first and second year respectively) than other three varieties. The second highest unit weight was recorded as 50.15 g and 62.16 g for variety $V_3$ while the lowest was recorded as 40.63 g and 49.58 g for $V_1$ in the first and second year, respectively. Like the bulb size, unit weight of $V_2$, $V_3$ and $V_4$ were comparable. In general, unit bulb weight gradually increased with the increasing of irrigation regimes. This result is in agreement with that of a study conducted by Sezen et al. (2008), high amount of soil moisture application leads to large photosynthesis area (plant height and large number of leaves), results to large bulb size and weight as well.

**Onion bulb and biomass yield**

Like yield contributing characters, variation in the amount of the applied water caused a significant ($P \leq 0.05$) variation in bulb and biomass yield of onion (Table 1). Irrespective of variety, bulb yield was found the highest when irrigation was applied on the basis of 120% ETo, while the least amount of applied water (60% ETo) resulted in the lowest bulb yield. Application of increasing amount of water per irrigation from 0.6 ETo to 1.2 ETo resulted in significant increase in bulb yield. The increase in yield per unit of applied water decreased with the increasing amount of applied water. The rate of increment was 24.32% from 0.6ETo to 0.8ETo, 14.23% from 0.8 ETo to 1.0 ETo, and only 11.87% from 1.0ETo to 1.2ETo. Bulb yield increased significantly at each irrigation level from 60% ETo to 100% ETo; however from 100% to 120% ETo the increase in BY was insignificant, which is consistent with the findings reported by Kang et al. (2002) and further increase in water regime from 120% to 140% failed to increase BY of onion rather yield was decreased. Thus water can be saved without significant reduction in yield by irrigating the crop at the level of 1.0 ETo and 1.2 ETo. In case of 0.8 ETo water regime, plant felt strees between two consecutive irrigations and that was the probable reason for lower BY as compared to 80% ETo and higher water regimes. Onions have been shown to be productive under frequent irrigations that allow little soil water depletion (Shock et al., 1998).

In case of variety, the highest bulb yield was obtained from variety $V_4$ followed by $V_3$ while variety $V_1$ gave the lowest yield that was identical with $V_2$. Bulb yield of onion ranged from 14.49 to 24.53 t/ha for $V_4$, from 13.15 to 22.04 t/ha for $V_{3,}$ 12.03 to 17.73 t/ha for $V_2$ and from 11.34 to 16.57 t/ha for $V_1$ with minimum in treatment 60% ETo and maximum value in treatment 120%

ETo. In the present study, the increased yield in sprinkler irrigation system was mostly due to the favorable effect of available soil moisture, uniform distribution of irrigation water during entire growth period. Another possible reason is continuous availability of moisture enhanced the availability and uptake of nutrients throughout the cropping period which resulted in better growth and bulb development. However, the yield of onion at 100% and 120% ETo was found to be non-significant which was probably due to the fact that irrigation at 100% ETo was adequate to provide sufficient soil moisture for optimum onion production. Effect of irrigation regimes on above-ground biomass yield followed almost similar trend like that of bulb yield (Table 1). Unlike bulb yield, the highest biomass yield was recorded under wettest treatment of 120% and 140% ETo and the least amount of applied water (0.6ETo) resulted in the lowest above ground biomass yield.

Table 1a: Yield and yield contributing parameters of onions under sprinkler irrigation with different water regimes during 2020 – 2021 growing season

| Treatment | Plant height (cm) | Leaves/plant (no) | Stem dia (mm) | Bulb length (mm) | Bulb dia (mm) | Unit bulb wt. (g) | Bulb yield (t/ha) | DM (kg/ha) |
|---|---|---|---|---|---|---|---|---|
| Irrigation levels | | | | | | | | |
| $I_1$ | 51.60 | 6.79 | 11.00 | 52.69 | 48.13 | 50.80 | 14.74 | 792.83 |
| $I_2$ | 55.67 | 6.94 | 12.38 | 57.26 | 51.51 | 60.67 | 18.19 | 847.17 |
| $I_3$ | 58.98 | 7.07 | 13.08 | 58.72 | 52.56 | 66.57 | 22.20 | 1018.75 |
| $I_4$ | 62.35 | 7.70 | 14.13 | 59.14 | 54.03 | 70.82 | 24.87 | 1112.21 |
| $I_5$ | 63.94 | 7.98 | 14.61 | 60.93 | 54.81 | 72.61 | 24.77 | 1251.21 |
| $LSD_{0.05}$ | 3.35 | 1.18 | 1.12 | 3.18 | 4.12 | 3.68 | 2.85 | 44.13 |
| CV (%) | 6.16 | 5.26 | 5.74 | 4.66 | 4.55 | 7.64 | 6.38 | 9.27 |
| Onion variety | | | | | | | | |
| $V_1$ | 54.21 | 7.09 | 12.74 | 49.16 | 50.49 | 47.92 | 16.02 | 958.63 |
| $V_2$ | 60.35 | 7.48 | 12.79 | 58.26 | 53.08 | 67.74 | 21.82 | 920.73 |
| $V_3$ | 60.57 | 7.35 | 13.36 | 57.75 | 51.48 | 62.97 | 20.74 | 1069.53 |
| $V_4$ | 58.89 | 7.26 | 13.28 | 65.81 | 53.78 | 78.55 | 25.23 | 1068.83 |
| $LSD_{0.05}$ | 3.78 | 1.46 | 1.04 | 4.72 | 4.09 | 3.55 | 1.86 | 33.68 |
| CV(%) | 5.21 | 4.68 | 5.14 | 6.26 | 5.82 | 7.22 | 5.47 | 8.38 |
| Irrigation x Variety | | | | | | | | |
| $V_1I_1$ | 47.33 | 6.70 | 10.80 | 43.60 | 45.80 | 35.59 | 11.74 | 720.00 |
| $V_1I_2$ | 52.20 | 6.87 | 12.33 | 48.73 | 50.93 | 46.31 | 14.26 | 854.67 |
| $V_1I_3$ | 53.93 | 6.94 | 12.40 | 49.63 | 51.97 | 50.97 | 17.18 | 1022.00 |
| $V_1I_4$ | 59.07 | 7.38 | 14.27 | 51.80 | 51.37 | 54.88 | 19.03 | 1001.33 |
| $V_1I_5$ | 58.53 | 7.58 | 13.90 | 52.03 | 52.37 | 51.87 | 17.92 | 1195.17 |
| $V_2I_1$ | 52.07 | 6.92 | 11.20 | 53.87 | 47.33 | 50.74 | 15.45 | 699.50 |
| $V_2I_2$ | 55.07 | 7.17 | 11.67 | 60.70 | 55.73 | 68.11 | 18.84 | 859.17 |
| $V_2I_3$ | 60.40 | 7.33 | 13.20 | 58.30 | 53.40 | 70.70 | 22.92 | 980.00 |
| $V_2I_4$ | 62.20 | 7.87 | 13.53 | 56.97 | 52.43 | 72.05 | 25.93 | 909.17 |
| $V_2I_5$ | 64.73 | 8.13 | 14.33 | 61.47 | 56.50 | 77.10 | 25.97 | 1155.83 |
| $V_3I_1$ | 53.13 | 6.87 | 10.87 | 52.30 | 46.47 | 51.72 | 14.73 | 779.50 |
| $V_3I_2$ | 58.60 | 6.93 | 13.53 | 57.03 | 48.23 | 59.09 | 18.15 | 824.00 |
| $V_3I_3$ | 60.40 | 7.13 | 13.13 | 59.73 | 53.10 | 66.16 | 21.94 | 1139.67 |
| $V_3I_4$ | 63.53 | 7.63 | 13.60 | 58.20 | 54.77 | 70.78 | 24.72 | 1229.17 |
| $V_3I_5$ | 66.10 | 8.17 | 15.67 | 61.50 | 54.83 | 67.09 | 24.17 | 1375.33 |
| $V_4I_1$ | 53.87 | 6.67 | 11.13 | 61.00 | 52.90 | 65.16 | 17.03 | 972.33 |
| $V_4I_2$ | 56.80 | 6.80 | 12.00 | 62.57 | 51.13 | 69.20 | 21.53 | 850.83 |
| $V_4I_3$ | 61.20 | 6.87 | 13.60 | 67.20 | 51.77 | 78.44 | 26.76 | 933.33 |
| $V_4I_4$ | 64.60 | 7.93 | 15.13 | 69.60 | 57.57 | 85.58 | 29.81 | 1309.17 |
| $V_4I_5$ | 66.40 | 8.04 | 14.53 | 68.70 | 55.53 | 94.37 | 31.02 | 1278.50 |
| $LSD_{0.05}$ | 4.16 | 1.21 | 1.16 | 4.64 | 4.44 | 7.64 | 2.06 | 65.34 |
| CV (%) | 5.21 | 4.68 | 5.14 | 6.26 | 5.82 | 7.22 | 5.47 | 8.38 |

Table 1b: Yield and yield contributing parameters of onions under sprinkler irrigation with different water regimes during 2021 – 2022 growing season

| Treatment | Plant height (cm0 | Leaves/plant (no) | Stem dia (mm) | Bulb length (mm) | Bulb dia (mm) | Unit bulb wt. (g) | Bulb yield (t/ha) |
|---|---|---|---|---|---|---|---|
| Irrigation levels | | | | | | | |
| $I_1$ | 52.28 | 6.57 | 12.12 | 49.11 | 44.67 | 49.44 | 18.65 |
| $I_2$ | 54.48 | 6.78 | 12.47 | 49.99 | 47.76 | 56.73 | 22.01 |
| $I_3$ | 57.05 | 7.38 | 13.83 | 52.94 | 49.83 | 62.50 | 25.09 |
| $I_4$ | 60.27 | 7.67 | 13.87 | 52.83 | 52.03 | 66.05 | 27.67 |
| $I_5$ | 60.52 | 7.77 | 15.90 | 54.67 | 53.58 | 68.67 | 27.16 |
| $LSD_{0.05}$ | 3.34 | 1.56 | 1.10 | 3.22 | 4.16 | 3.66 | 2.56 |
| CV (%) | 5.30 | 7.16 | 6.84 | 4.79 | 4.62 | 8.33 | 6.44 |
| Onion variety | | | | | | | |
| $V_1$ | 53.28 | 7.15 | 13.16 | 42.55 | 47.79 | 49.58 | 17.72 |
| $V_2$ | 58.25 | 6.97 | 13.40 | 54.52 | 50.72 | 61.69 | 25.38 |
| $V_3$ | 59.05 | 7.41 | 14.15 | 50.24 | 48.33 | 63.16 | 26.61 |
| $V_4$ | 57.09 | 7.40 | 13.84 | 60.32 | 51.46 | 63.29 | 26.75 |
| $LSD_{0.05}$ | 4.82 | 2.58 | 1.10 | 4.82 | 4.12 | 3.65 | 1.52 |
| CV(%) | 5.23 | 4.78 | 6.32 | 6.36 | 6.54 | 7.28 | 5.44 |
| Irrigation x Variety | | | | | | | |
| $V_1I_1$ | 49.73 | 6.60 | 12.93 | 37.07 | 41.27 | 39.83 | 14.01 |
| $V_1I_2$ | 50.20 | 7.63 | 11.73 | 40.73 | 45.33 | 45.29 | 16.49 |
| $V_1I_3$ | 52.27 | 7.53 | 12.67 | 45.20 | 49.00 | 52.49 | 18.30 |
| $V_1I_4$ | 55.93 | 7.20 | 12.73 | 44.03 | 50.50 | 51.81 | 20.13 |
| $V_1I_5$ | 58.27 | 7.67 | 15.73 | 45.73 | 52.83 | 58.45 | 19.68 |
| $V_2I_1$ | 54.87 | 6.13 | 11.13 | 52.47 | 45.47 | 46.59 | 19.17 |
| $V_2I_2$ | 56.53 | 6.53 | 12.00 | 52.53 | 48.37 | 58.55 | 24.09 |
| $V_2I_3$ | 58.33 | 7.13 | 14.20 | 55.40 | 51.03 | 62.11 | 25.56 |
| $V_2I_4$ | 61.13 | 7.47 | 13.53 | 55.73 | 53.80 | 68.67 | 28.25 |
| $V_2I_5$ | 60.40 | 7.60 | 16.13 | 56.47 | 54.93 | 72.53 | 29.84 |
| $V_3I_1$ | 53.93 | 6.87 | 12.27 | 46.70 | 43.90 | 58.01 | 21.48 |
| $V_3I_2$ | 56.27 | 6.87 | 13.47 | 49.50 | 46.87 | 63.75 | 23.85 |
| $V_3I_3$ | 59.47 | 7.67 | 14.80 | 50.23 | 48.17 | 68.46 | 27.77 |
| $V_3I_4$ | 62.53 | 7.67 | 15.07 | 50.23 | 50.33 | 75.83 | 30.40 |
| $V_3I_5$ | 63.07 | 8.00 | 15.13 | 54.53 | 52.37 | 74.73 | 29.56 |
| $V_4I_1$ | 50.60 | 6.53 | 12.13 | 60.20 | 48.03 | 53.34 | 19.96 |
| $V_4I_2$ | 54.93 | 7.13 | 12.67 | 57.20 | 50.47 | 59.32 | 23.61 |
| $V_4I_3$ | 58.13 | 7.20 | 13.67 | 60.93 | 51.13 | 66.94 | 28.73 |
| $V_4I_4$ | 61.47 | 7.33 | 14.13 | 61.33 | 53.47 | 67.90 | 29.56 |
| $V_4I_5$ | 60.33 | 7.80 | 16.60 | 61.93 | 54.20 | 68.96 | 31.56 |
| $LSD_{0.05}$ | 4.10 | 3.12 | 1.19 | 4.68 | 4.96 | 7.75 | 2.16 |
| CV (%) | 5.26 | 4.76 | 6.02 | 6.38 | 6.56 | 7.26 | 5.14 |

**Leaf area and above-ground dry matter**

Leaf area (LA) was positively affected by increasing level of water regimes. Irrespective of variety, application of water with higher water regimes (120% and 140%ETo) significantly increased the leaf area of onion compared with lower water regime (60% ETo). Application of water at 60% ETo produced the lowest leaf area while water application at 120% or 140% ETo regime produced the highest LA (Figure 1) at different days after transplanting (DAP). Starting from 35 DAP, increment of LA was almost linear up to 60 DAP, thereafter LA started to decrease. After the maximum leaf area was reached at 60 DAP, the following stage lasted around 15 days, thereafter it started to decrease. Increasing rate was faster in early stage than mid stage and at the later stage it decreased as the leaves started to die. Across the variety, about 170% increment in LA was recorded from 35 to 45 DAP and from 45 to 60DAP, it was only about 29%. Rate of increment in LA was somewhat different in magnitude among the varieties. On average over water regimes, it ranged between 33% and 138% for the variety $V_1$, between 15% and 184% for the variety $V_2$, between 31% and 193% for the variety $V_3$ and between 36% and 162% for the variety $V_4$ with maximum values at early stage (from 35 to 45 DAP) and minimum values at mid stage (from 45 to 60 DAP). Among the varieties, $V_3$ and $V_4$ had the significantly higher LAs at all water regimes than the varieties $V_2$ and $V_1$ which had the lowest LA. The differences in LA between $V_1$ and $V_2$ were very marginal and insignificant and so as to between $V_3$ and $V_4$. The difference in LA among the water regimes was observed to be higher for $V_3$ and $V_4$ than other two varieties, indicating that the variety $V_3$ and $V_4$ were much sensitive to water.

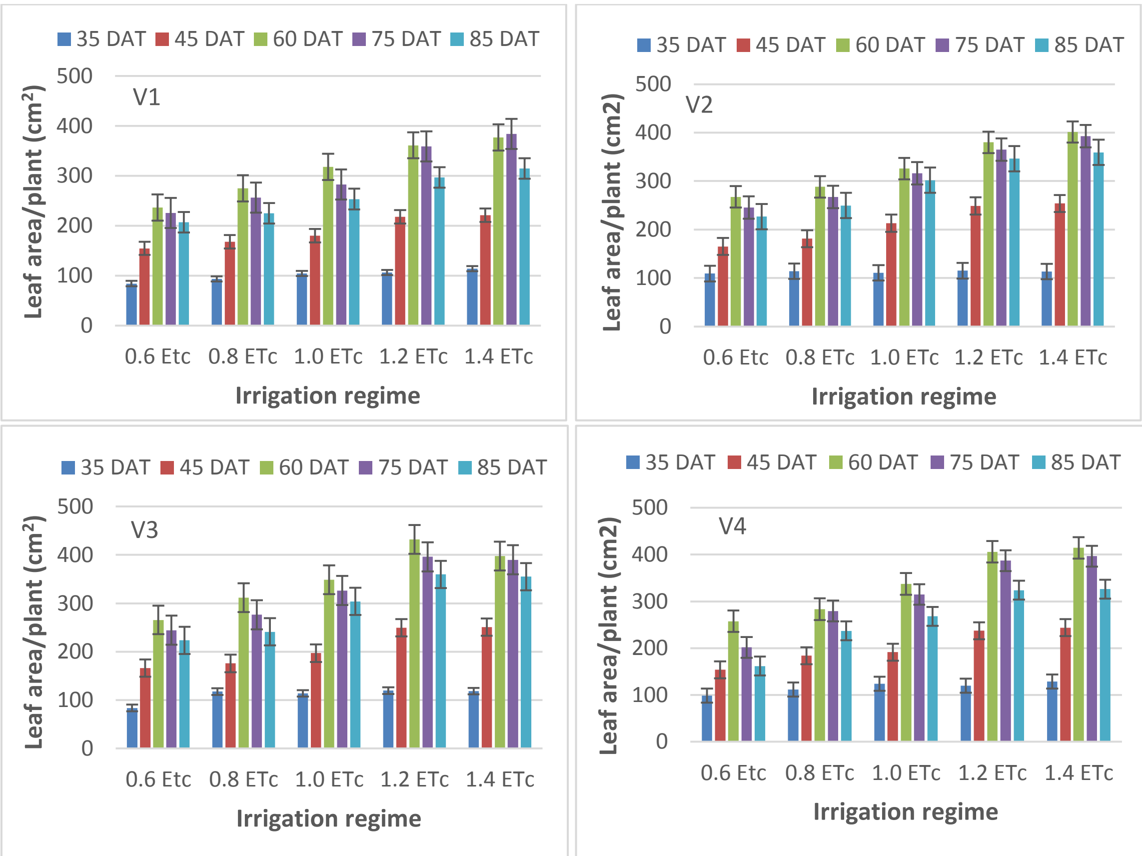


Fig-1a. Leaf area of onion varieties affected by water regimes at different days after transplanting (DAT).

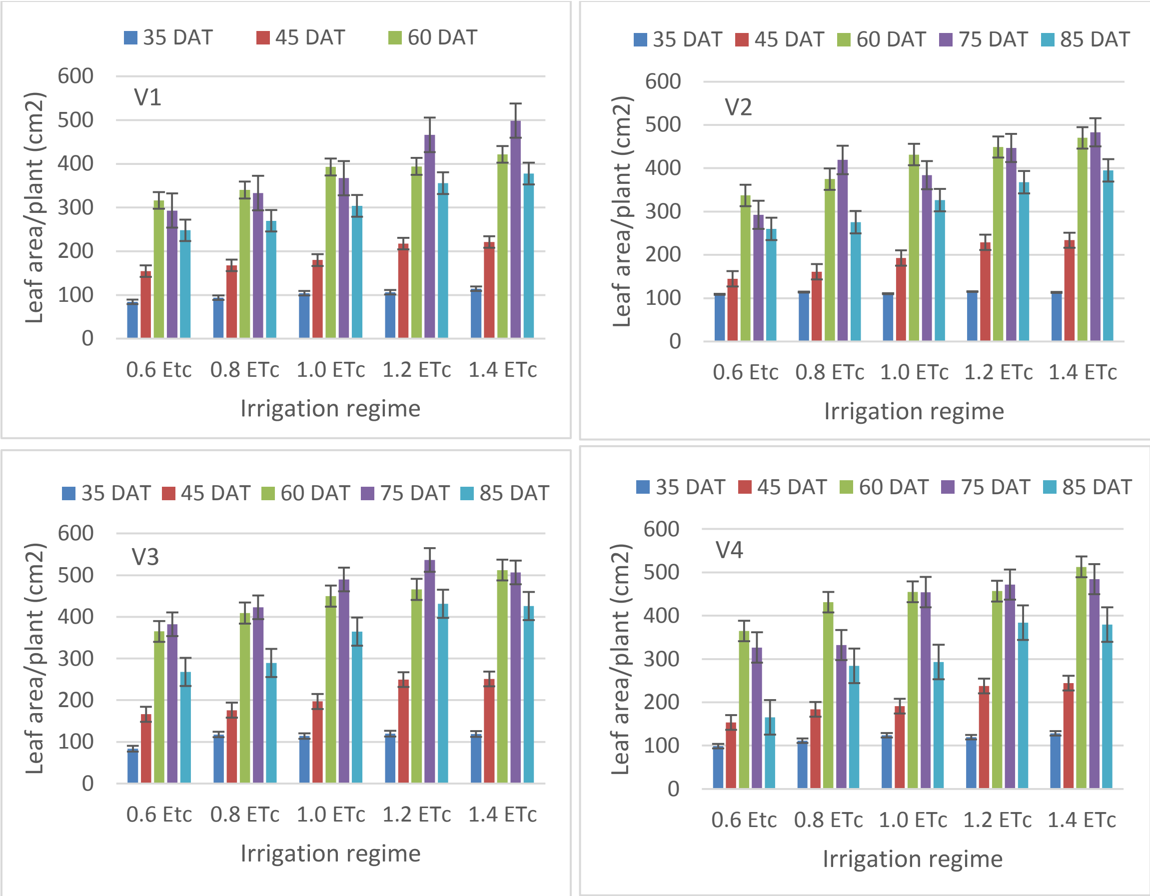


Fig-1a. Leaf area of onion varieties affected by water regimes at different days after transplanting (DAT).

Unlike LA, the above-ground dry matter, ADM, of onion increased gradually during the initial growth stage (35 – 45 DAT) and rapidly during the mid-stage to attain the peak at 60 DAT (Fig. 2); thereafter it maintained a plateau up to 75 DAT and then started to decrease. Dry matter accumulation was found faster during mid-stage (45 – 60 DAT) than during early stage (35 – 45 DAT). ADM decreased at the later stage due to bulb formation and senescence of the plants. That is, after 60 DAT, dry matter accumulated in the plants translocated and contributed much to the formation of onion bulb and thereby ADM gradually decreased. Like LA, hereto, ADM per plant was found higher in wet regime 120 – 140% ETc and lower in dry water regime of 60%ETc. At all levels of water regimes, significantly higher ADM was recorded in $V_4$, $V_3$ and $V_2$ compared to $V_1$. The value of ADM per plant ranged from 1.98 to 3.71 g, 1.56 to 3.65 g, 1.99 to 4.22 g, and 1.78 to 4.49 g for $V_1$, $V_2$, $V_3$ and $V_4$, respectively, in the first year, either at 120% ETc or at 140% Etc. The trend was same in the second year but with higher magnitude. On average, ADM increased at a faster rate of 135% at the mid stage and at a slower rate of 48% at the early stage.

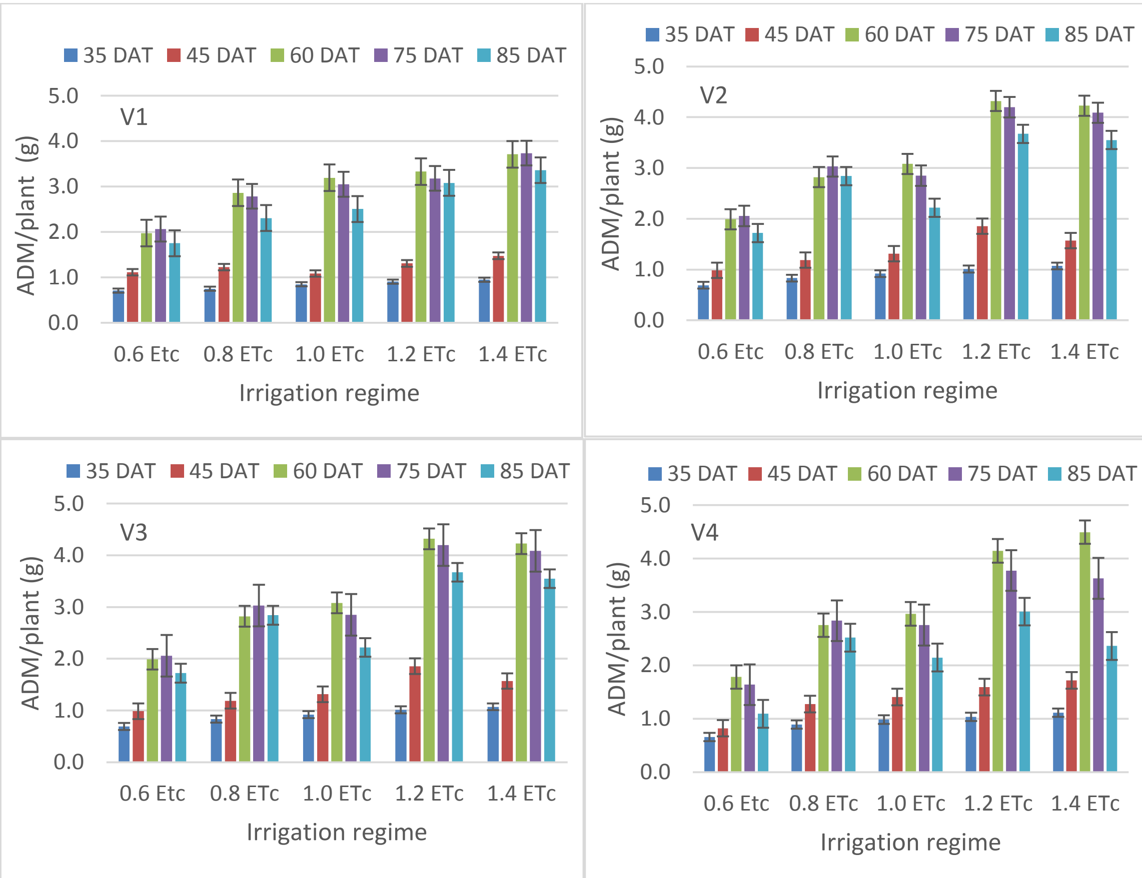


**Fig-2a** Above-ground dry matter of onion varieties affected by water regimes at different days after transplanting (DAT) during the growing season of 2020- 2021.

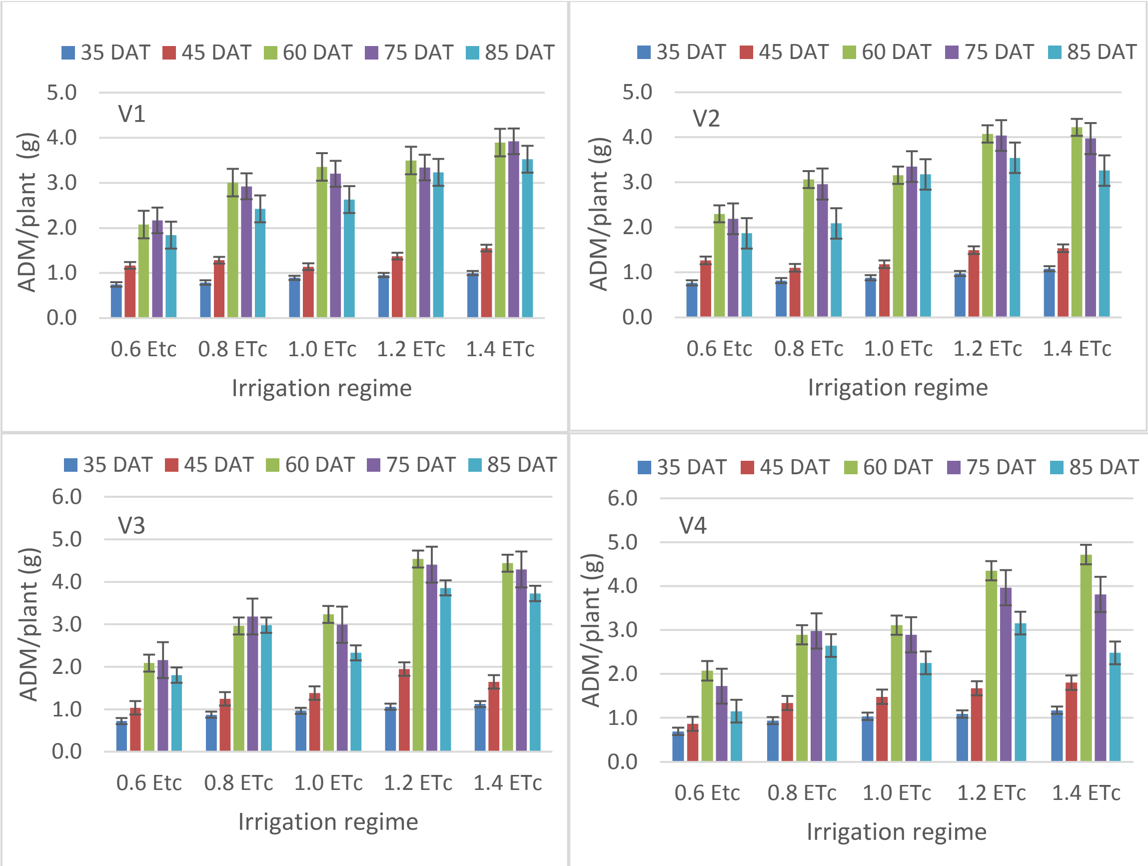


**Fig-2b** Above-ground dry matter of onion varieties affected by water regimes at different days after transplanting (DAT) during the growing season of 2021- 2022.

**Yield response factor (Ky)**

The relationship between evapotranspiration deficit (1- ETa/ETm) and yield depression (1 – Ya/Ym) is always linear (Doorenbos and Kassam, 1979), with a slope called the yield response factor (Ky). Crop yield response factor (Ky) for different onion varieties showed statistically significant linear relationship between the decrease in relative evapotranspiration deficit and the decrease in relative yield (Figure 2).The Ky values for total onion growing season ranged between 0.93 to 1.08, the lowest and the highest being for $V_1$ and $V_4$ variety, respectively ((Figure 3). Ky value for $V_4$ was the highest (1.13) which is comparable to $V_2$ (1.05) and $V_3$ (1.12) while Ky value for $V_1$ was the lowest (0.90). The greater Ky value of $V_2$, $V_3$ and $V_4$ than the variety $V_1$ indicates that the variety $V_2$, $V_3$ and $V_4$ are more responsive to irrigation, that is relative decrease in evapotranspiration resulted in more reduction in yield. The determined Ky values are very close to 1.10 that reported by Doorenbos and Kassam (1986) and Kadayifci et al. (2005). These findings revealed that onion is very sensitive to soil water stress during the total growing season and hence onion should be grown with adequate irrigation for obtaining a good yield. For variety $V_1$, Ky value was less than unity indicated that this variety can tolerate a mild stress without a considerable yield loss. The higher Ky values for $V_2$, $V_3$ and $V_4$ indicate that the crop will have a greater yield loss when

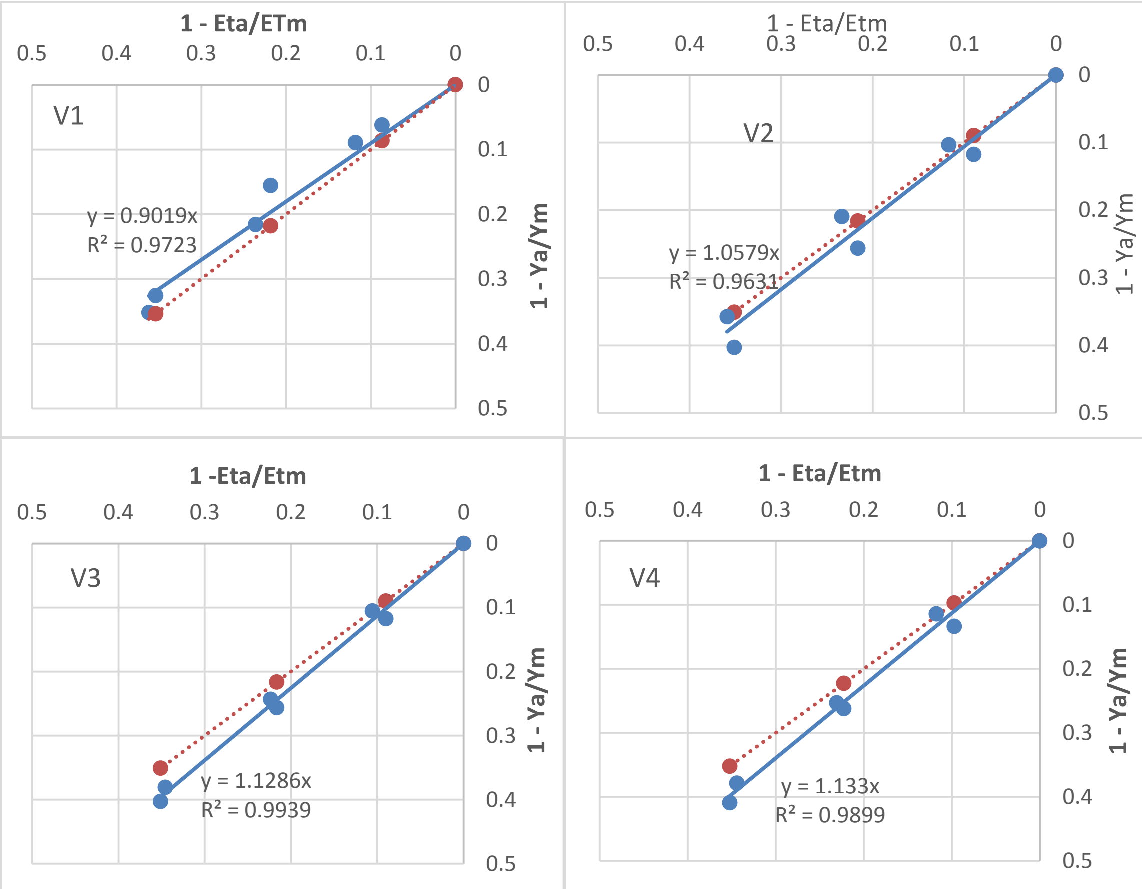


Fig. 3. Relationship between relative yield decrease and relative crop evapotranspiration decrease for onion (full line) and reported by Doorenbos and Kassam (dotted line).

the crop water requirements are not met. Therefore, DI practices should be avoided for Ky values that are more than unity. This conclusion is in line with a statement given by Doorenbos and Kassam (1986) who underline that Ky >1.0 indicates the decrease in yield is proportionally greater with increase in water deficit. Considering Ky as a limiting factor, 80% ETo application was a marginal for $V_1$ and $V_2$ and 100% ETo for $V_3$ and $V_4$, beyond that yield losses are unbearable. These Ky values for onion could be used for planning, design and operation of irrigation projects which allows quantifications of water supply and water use in terms of crop yield and total production for the project area.

**Seasonal water use and water productivity**

Total water used by the crop was equal to the applied irrigation water, effective rainfall plus contribution by soil water during the growing season. Irrespective of variety, the amount of water applied to the crop ranged from 127 and 269 mm in the first year and from 133 to 258 mm in the second year with minimum in the 60% ETo water regime and maximum in the wettest water regime of 140% ETo (Table 2a). Seasonal evapo-transpiration (SET)

Table 2a. Water productivity of onion varieties under different irrigation regimes during rabi season of 2020 - 2021

| Treatment | Irrigation for plant estb (mm) | Irrigation after plant estb (mm) | ER (mm) | SMC (mm) | Drainage (mm) | SET (mm) | Yield (t/ha) | WP (kg/m3) |
|---|---|---|---|---|---|---|---|---|
| Variety: V1 (BARI Piaj-1) | | | | | | | | |
| I1 | 20 | 107 | 2 | 20 | 0 | 149 | 11.74 | 7.89 |
| I2 | 20 | 142 | 2 | 15 | 0 | 179 | 14.26 | 7.95 |
| I3 | 20 | 178 | 2 | 14 | 0 | 214 | 17.18 | 8.03 |
| I4 | 20 | 213 | 2 | 11 | 4 | 242 | 19.03 | 7.86 |
| I5 | 20 | 249 | 2 | 5 | 7 | 269 | 17.92 | 6.66 |
| Variety: V2 (Lal Teer Hybrid) | | | | | | | | |
| I1 | 20 | 107 | 2 | 21 | 0 | 150 | 15.45 | 10.32 |
| I2 | 20 | 142 | 2 | 16 | 0 | 180 | 18.84 | 10.44 |
| I3 | 20 | 178 | 2 | 16 | 0 | 216 | 22.92 | 10.61 |
| I4 | 20 | 213 | 2 | 11 | 2 | 244 | 25.93 | 10.63 |
| I5 | 20 | 249 | 2 | 8 | 7 | 272 | 25.97 | 9.61 |
| Variety: V3 (Taherpuri King) | | | | | | | | |
| I1 | 20 | 107 | 2 | 21 | 0 | 150 | 14.73 | 9.83 |
| I2 | 20 | 142 | 2 | 17 | 0 | 181 | 18.15 | 10.00 |
| I3 | 20 | 178 | 2 | 15 | 0 | 215 | 21.44 | 10.13 |
| I4 | 20 | 213 | 2 | 12 | 3 | 244 | 24.72 | 10.21 |
| I5 | 20 | 249 | 2 | 7 | 7 | 271 | 24.17 | 8.94 |
| Variety: V4 (BARI Piaj-1) | | | | | | | | |
| I1 | 20 | 107 | 2 | 21 | 0 | 150 | 17.03 | 11.37 |
| I2 | 20 | 142 | 2 | 16 | 0 | 180 | 21.53 | 11.93 |
| I3 | 20 | 178 | 2 | 15 | 0 | 215 | 26.56 | 12.17 |
| I4 | 20 | 213 | 2 | 12 | 2 | 245 | 29.81 | 12.45 |
| I5 | 20 | 249 | 2 | 7 | 6 | 272 | 31.02 | 11.40 |

varied, to a greater extent, with the variation in amount of water application and, to a lesser extent, with the varieties. Though all varieties received same amount of irrigation water, water productivity varied remarkably as variety $V_2$, $V_3$ and $V_4$ produced significantly higher yield than other two varieties. Seasonal evapotranspiration was increased with the applied irrigation water and on average it ranged from 149 to 269 mm for $V_1$, from 150 to 272 mm for $V_2$, from 150 to 271 mm for $V_3$ and from 150 to 272 mm for $V_4$ under 60% ETo and 140% ETo water regimes, respectively, in the first year while in the following year, it ranged from 181 to 285 mm for $V_1$, from 184 to 287 mm for $V_2$, from 183 to 288 mm for $V_3$ and from 182 to 288 mm for $V_4$ under 60% ETo and 140% ETo water regimes.

Table-2b. Water productivity of onion varieties under different irrigation regimes during the rabi season of 2021 – 2022

| Treatment | Irrigation for plant estb. (mm) | Irrigation after plant estb. (mm) | Effective rainfall (mm) | SMC | Drainage (mm) | SET (mm) | Yield (t/ha) | WP (kg/m$^3$) |
|---|---|---|---|---|---|---|---|---|
| Variety: $V_1$ (BARI Piaj-1) | | | | | | | | |
| $I_1$ | 20 | 113.59 | 36 | 12 | 0 | 181.59 | 14.01 | 7.71 |
| $I_2$ | 20 | 144.79 | 36 | 8 | 0 | 208.79 | 16.49 | 7.90 |
| $I_3$ | 20 | 176 | 36 | 7 | 0 | 239 | 18.30 | 7.66 |
| $I_4$ | 20 | 207.18 | 36 | 5 | 4 | 264.18 | 20.13 | 7.62 |
| $I_5$ | 20 | 238.38 | 36 | 2 | 11 | 285.38 | 19.68 | 6.90 |
| Variety: $V_2$ (Taherpuri Super, Metal) | | | | | | | | |
| $I_1$ | 20 | 113.59 | 36 | 15 | 0 | 184.59 | 19.17 | 10.38 |
| $I_2$ | 20 | 144.79 | 36 | 9 | 0 | 209.79 | 24.09 | 11.48 |
| $I_3$ | 20 | 176 | 36 | 8 | 0 | 240 | 25.56 | 10.65 |
| $I_4$ | 20 | 207.18 | 36 | 6 | 4 | 265.18 | 28.25 | 10.65 |
| $I_5$ | 20 | 238.38 | 36 | 3 | 10 | 287.38 | 29.84 | 10.38 |
| Variety: $V_3$ (Taherpuri King, Lal Teer) | | | | | | | | |
| $I_1$ | 20 | 113.59 | 36 | 14 | 0 | 183.59 | 20.08 | 10.94 |
| $I_2$ | 20 | 144.79 | 36 | 8 | 0 | 208.79 | 23.85 | 11.42 |
| $I_3$ | 20 | 176 | 36 | 10 | 0 | 242 | 27.77 | 11.48 |
| $I_4$ | 20 | 207.18 | 36 | 7 | 2 | 268.18 | 30.40 | 11.34 |
| $I_5$ | 20 | 238.38 | 36 | 3 | 9 | 288.38 | 29.56 | 10.25 |
| Variety: $V_4$ (BARI Piaj-4) | | | | | | | | |
| $I_1$ | 20 | 113.59 | 36 | 13 | 0 | 182.59 | 19.96 | 10.93 |
| $I_2$ | 20 | 144.79 | 36 | 11 | 0 | 211.79 | 23.61 | 11.15 |
| $I_3$ | 20 | 176 | 36 | 8 | 0 | 240 | 28.73 | 11.97 |
| $I_4$ | 20 | 207.18 | 36 | 6 | 6 | 263.18 | 31.90 | 12.12 |
| $I_5$ | 20 | 238.38 | 36 | 4 | 10 | 288.38 | 29.56 | 10.25 |

In the present study, under different sprinkler irrigation regimes, water productivity ranged between 6.66 and 8.03 kg/m$^3$ for $V_1$ with maximum value in 100% ETo, between 9.61 and 10.61 kg/m$^3$ for $V_{2,}$ between 8.94 and 10.21 kg/m$^3$ for V3 and between 11.37 and 12.45 kg/m$^3$ with maximum value in 120% ETo and minimum value in 60% or 140% ETo. Unlike $V_1$, the highest WP for $V_4$, $V_3$ and $V_2$ were obtained from 120% ETo treatment rather than the treatment 100% ETo. This indicates that variety $V_2$, $V_3$ and $V_4$ are more responsive to irrigation even at higher water regime. In this case, the greater increase in bulb yield than that of SET was responsible for the higher magnitude of WP than other two varieties. In case of $V_1$, WP increased up to 100% Eto; thereafter it decreased with further increasing of irrigation regime. But for $V_2$, $V_3$ and $V_4$, WP was still increasing with the increasing in irrigation regime and attained the highest level under 120% ETo. This was due to the fact that, for $V_1$, up to 100% ETo the relative increment of bulb yield was greater than the relative increment of SET. For variety $V_2$, $V_3$ and $V_4$, relative increment in yield was always higher than relative increment of SET. However, for all levels of irrigation regimes, variety $V_4$ had the higher water productivity closely followed by $V_2$ and $V_3$ while the variety $V_1$ had the lower WPs due to the greater decrease in bulb yield than that of SET.

### Changes in soil moisture storage

Changes in soil moisture storage during the growing period were always higher under lower regime than under higher regime irrigation treatments (Fig. 3a). The least amount of irrigation

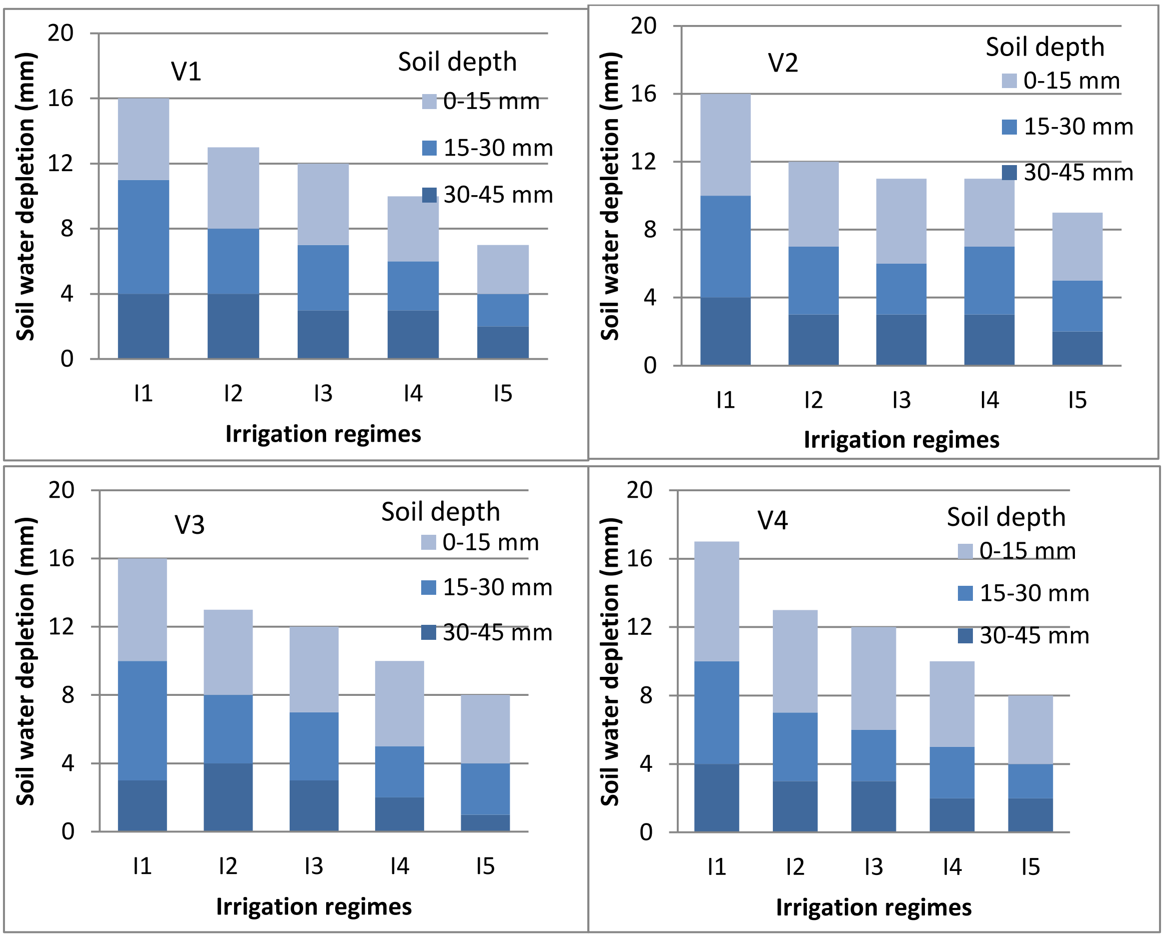


Fig. 3a. Soil water depletion pattern by soil depth under different water regimes

applied under lowest irrigation regime of 0.6 ETo may be the reason for the higher changes in soil moisture storage. Under lower irrigation regimes, the water depletion from the first layer (0–15 cm) was maximum (12 mm). When the surface layer (0–15 cm) became dry, the 15– 30 cm layer was the primary source of water used by the plant, due either to upward movement of water to the roots, or by direct water uptake by the roots within this depth. In wetter regime treatments, pattern was almost same as of drier regime treatments with difference in magnitude. But under driest irrigation regime (60% ETo), the highest changes occurred in the mid layer (15–30 cm) followed by that obtained in the 0–15 cm layer. This may be due to the fact that under this irrigation treatments a small amount of water was applied at each irrigation, which caused soil wetness down to 15 cm depth, leaving mid layer soil (15–30 cm) drier. As a result, moisture depletion was more in this layer than top layer. Difference in soil water storage between these two layers increased from wetter to drier irrigation regimes (120% ETo to 60% ETo) due to decrease in amount of water applied at each irrigation.

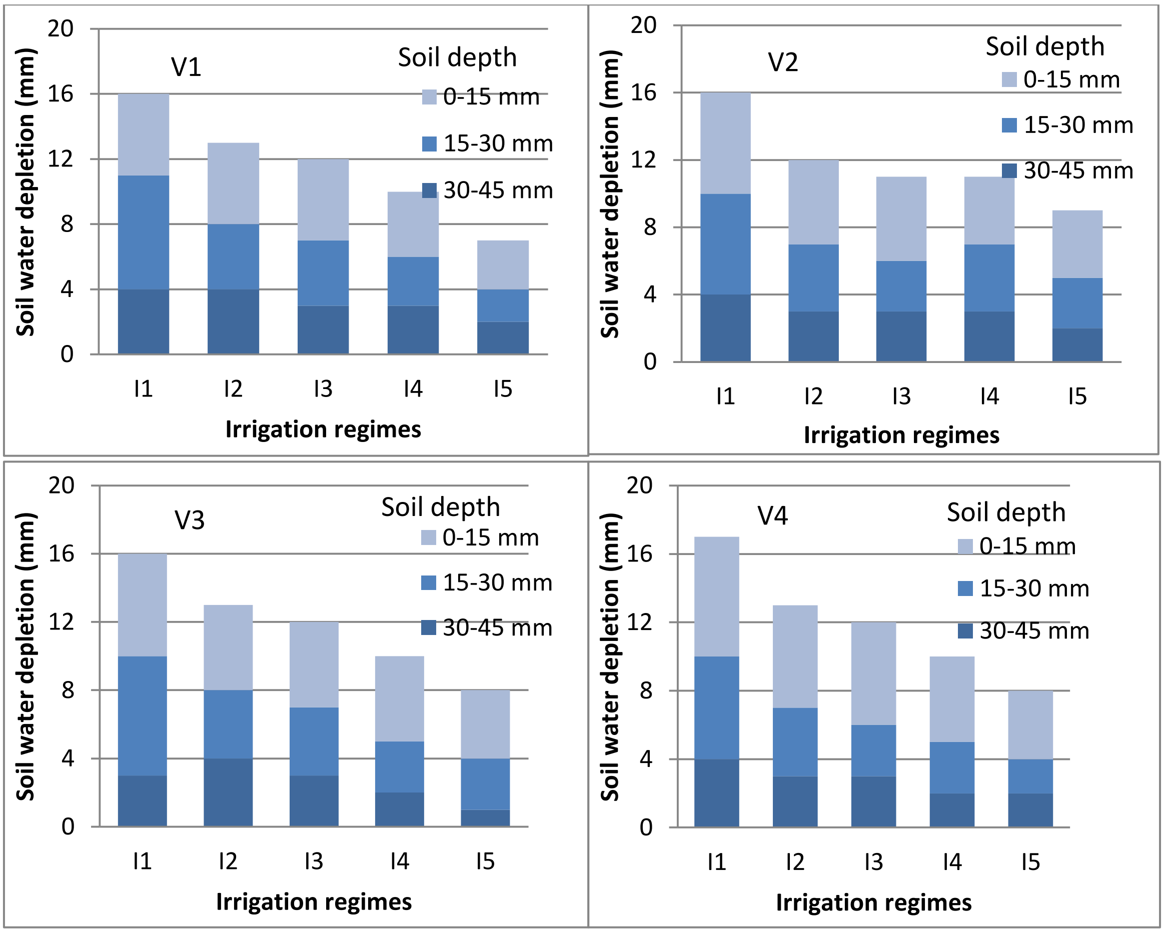


Fig-3b. Soil water depletion pattern by soil depth under different water regimes

## Conclusions

Sprinkler irrigation with different water regimes had a significant effect on the growth and bulb yield of onion. Onion bulb yield under sprinkler irrigation with higher water regimes was significantly higher than the yield recorded under lower irrigation regimes. For all varieties, bulb yield of onion increased gradually with increasing of water regime from 60% to 120% ETo. For $V_1$ and $V_2$, application of water beyond 100% ETo water regime increased the yield insignificantly, but it was significant for the variety $V_3$ and $V_4$. The yield obtained from $V_3$ and $V_4$ was always higher under all levels of irrigation regimes than that obtained from $V_1$ and $V_2$. Bulb yield obtained from $V_4$ and $V_3$ were identical and so does that obtained from $V_1$ and $V_2$. The amounts of water used for evapotranspiration varied little among varieties and much (157 – 272 mm) among irrigation regimes with minimum at 60% ETo and maximum at 140% ETo water regime. In case of $V_1$ and $V_2$, application of water helped to increase the WP up to 80% ETo; thereafter it started to decrease, while for the variety $V_3$ and $V_4$ it continued to increase even at higher water regime of 120% ETc. Values of Ky determined for the whole growing season was found higher for $V_3$ (Ky 1.12) and $V_4$ (1.13) than other two varieties (0.90 for $V_1$ and 0.92 for $V_2$). The higher WP and Ky indicate that variety $V_3$ and $V_4$ are highly responsive to irrigation. The values of Ky and WP can be a good basis for onion growers in relation to the optimum irrigation water use and utilization of irrigation systems, and also for improving the production technology of the crop.

## Conclusions

Sprinkler irrigation with different water regimes had a significant effect on the growth and bulb yield of onion. Onion bulb yield under sprinkler irrigation with higher water regimes was significantly higher than the yield recorded under lower irrigation regimes. For all varieties, bulb yield of onion increased significantly with increasing of water regime from 60% to 120% ETo. For $V_1$, application of water beyond 100% ETo water regime increased the yield insignificantly, but it was significant for the variety $V_2$, $V_3$ and $V_4$. The yield obtained from $V_2$, $V_3$ and $V_4$ was always higher under all levels of irrigation regimes than that obtained from $V_1$. The variety $V_4$ produced the highest yield of 31.02 t/ha under 120% ETo regime closely followed by the yield of 25.97 t/ha obtained from $V_2$ and 24.72 t/ha obtained from $V_3$. Yield obtained from BARI Piaj-1 ($V_1$) was the lowest (19.03 t/ha). The amounts of water used for evapotranspiration under different irrigation regimes ranged from 149 to 269 mm, 149 to 270 mm, 150 to 270 mm and 150 to 272 mm, respectively, for $V_1$, $V_2$, $V_3$ and $V_4$ with minimum at 60% ETo and maximum at 140% ETo water regime. In case of $V_1$, application of water helped to increase the WP up to 100% ETo; thereafter it started to decrease, while for the varieties $V_2$, $V_3$ and $V_4$ it continued to increase even at higher water regime of 140% ETo. Values of Ky determined for the whole growing season was found higher for $V_4$ (1.08), $V_3$ (Ky: 1.05) and $V_2$ (Ky: 1.044) than $V_1$ (BARI Piaj-1). The higher WP and Ky indicate that variety $V_2$, $V_3$ and $V_4$ are highly responsive to irrigation. The values of Ky and WP can be a good basis for onion growers in relation to the optimum irrigation water use and utilization of irrigation systems, and also for improving the production technology of the crop.

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## EFFECT OF FERTILIZER AND IRRIGATION FREQUENCY ON THE YIELD AND QUALITY OF EXPORT AND PROCESSING POTATO

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### Abstract

*Despite growing demand in home and abroad, Bangladesh lacks in producing export and processing quality potato due to varietal constraints and to a lesser extent, absence of apposite cultural practices. Proper irrigation and nutrient management can play a vital role in achieving higher productivity and quality of potato. With these perspectives, a field experiment was conducted at the research field of Irrigation and Water Management Division of the Bangladesh Agricultural Research Institute, Gazipur during 2020 – 2021 and 2021 – 2022 to evaluate the effects of fertilizer and irrigation on dry matter content, tuber yield and water productivity of an export and processing potato variety (BARI Alu-25). The treatments consisted of nine combinations of three fertilizers levels and three irrigation levels. Three fertilizer levels were $F_1$: Recommended fertilizer dose, $F_2$: Recommended dose with 75% MOP + 25% SOP + Vermicompost @2t/ha, $F_3$: Recommended dose with 50% MOP + 50% SOP. Similarly, three irrigation levels were $I_1$: 3 irrigations at 30, 45 and 60 days after planting (DAP), $I_2$: 4 Irrigations at 30, 45, 60 and 75 DAP and $I_3$: 4 Irrigations at 30, 45, 60 and 80 DAP. All irrigations were applied up to field capacity (FC), except last irrigations that received water 50% of FC at 75 and 80 DAP. The results indicate that fresh tuber yields of potato were not significantly influenced either by the irrigation treatments or by the fertilizer treatments. Due to late replanting, tuber yields were considerably lower in second season than first season. Water productivity also found higher in first season that ranged from 11.87 to 12.74 kg/m$^3$ under $I_1$, from 11.66 to 13.0 kg/m$^3$ under $I_2$, and 11.63 to 11.98 kg/m$^3$ under $I_3$ irrigation regimes with minimum values in $F_1$ and maximum in $F_2$ while in the second season it ranged from 8.6 to 9.2, 8.2 to 9.6 and 8.4 to 9.5 kg/m$^3$, respectively, for $I_1$, $I_2$ and $I_3$ water regimes. The fertilizer treatment $F_2$ produced slightly higher tuber yield and dry matter content compared to $F_1$ and $F_3$ in both the years. While the trivially higher yield was obtained from the irrigation treatment $I_2$ where last irrigation was applied at 75 DAP up to 50% of FC. Thus, the combination of $I_2$ and $F_2$ contributed the highest tuber yield, dry matter content and water productivity compared to other combinations of irrigation and fertilizer.. These results are of considerable importance to the growers of potato and may be preferred for growing export and processing potato in Bangladesh.*

### Introduction

Potato is a tuber crop that plays an important role in feeding people of the world and consumed daily by millions of people from diverse cultural backgrounds (Ahmadi et al., 2014). Potatoes are processed into a great variety of products, including cooked products, par-fried, French fries, chips, starch. Worldwide, potato is the most important agricultural food crop after cereals, like wheat, rice and maize is a high yielding crop. It is a cheap source of energy due to its large carbohydrate content (13 to 23%) (Haase, 2003; Ahmadi et al., 2014), as well as containing vitamins B and C and minerals. Moreover potato is also used in many industries like textile and alcohol production (Abdeldagir et al., 2003). Exporting potato by increasing its yield and quality may keep an important role on economic development of Bangladesh. But potato farmers in Bangladesh often struggle to export their produce as the potato they produce lacks in

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quality and fails to meet the standard required for export and processing as well. One of the important quality parameters considered for export and processing is dry matter content in tuber. Potato with higher dry matter content, preferred for both export and processing purposes, lacks in Bangladesh due varietal and other constraints like climate, soil, growing duration, irrigation and nutrient management, etc. Potato tubers intended for chips should contain 20-22% of dry matter and 14-17% of starch, and for crisps 20-25% of dry matter and 16-20% of starch (Lisińska 2000, Zgórska and Frydecka-Mazurczyk 2002, Grudzińska *et al.* 2016). Water is a basic requirement for early plant growth and tuber development. It is also related to dry matter content of the tuber. Potato plants are sensitive to water stress, and soil moisture is one of the important factors affecting the quantity and quality of tubers yield. Bao-Zhong *et. al.*,(2003) noted that tubers yield increased by increasing the amount of irrigation water, while the specific weight of tubers dropped. Harvesting or maturity also directly affects dry matter content. So, it is necessary to find out the optimum irrigation scheduling and harvesting time in order to maximize the economic return from exporting as well as processing. Dry matter content is important for both fresh markets and processing. Tubers with dry matter above 18-20% tend to be more susceptible to bruising and tubers disintegrate more readily when cooked. However, for processing high dry matter content is required to achieve a good fry color and often 20-25% is specified. Nitrogen, potassium and magnesium can all have influences on tuber dry matter content (Sarker et al., 2019). Nitrogen is often the limiting nutrient to achieve higher tuber yields (Marshall, 2007) but excessive amounts of N may be detrimental to quality traits (Bucher & Kossmann, 2007). While the optimal rate of N is not detrimental to DM production and content (Stark & Love, 2003). Potassium is essential for synthesis of sugars and starch and for translocation of carbohydrates (Singh et al., 1996). It also plays an important role for maintaining tone and vigor of the plants. The form of potassium has an effect on dry matter. Sulphate of potash - SOP (potassium sulphate) can achieve higher dry matters than muriate of potash - MOP (potassium chloride) and therefore is frequently the preferred form for processing potatoes. This is due to the chloride in the muriate of potash having a negative effect on tuber dry matter content. Other crop management practices influencing dry matter content like selecting the right variety to meet dry matter production needs; selecting quality seed with less risk of disease; avoiding fields, with adverse factors such poor drainage or low water holding capabilities; ensuring blight spray programs are effective; scheduling irrigation to maximize quality characteristics; harvesting early, thereby minimizing late disease ingress or tuber deterioration. With these viewpoints, this study was intended to find out the appropriate irrigation and fertilizer management for higher tuber yield, dry matter content and quality of processing potato.

## Materials and Methods

The study was conducted at the research field of Irrigation and Water Management (IWM) Division of Bangladesh Agricultural Research Institute (BARI) in Gazipur during the rabi season (November-February) of 2020 - 2021 and 2021 - 2022. The soil was silt clay loam with an average field capacity (FC) of 28.4% (weight basis) and mean bulk density of 1.44 g $cm^{-3}$ over 0-45 cm soil profile. The experiment was laid out in randomized complete block design (RCBD) with nine treatments replicated thrice.

The treatments consisted of nine combinations of three fertilizers levels and three irrigation levels. Three fertilizer levels were:

$F_1$: Recommended fertilizer dose
$F_2$: Recommended dose with 75% MOP + 25% SOP + Vermicompost @2t/ha
$F_3$: Recommended dose with 50% MOP + 50% SOP

Three irrigation levels were:

$I_1$: 3 irrigations at 30, 45 and 60 DAP
$I_2$: 4 irrigations at 30, 45, 60 and 75 DAP (Last irrigation upto 50%FC) and
$I_3$: 4 irrigations at 30, 45, 60 and 75 DAP (Last irrigation upto 50%FC)

At each irrigation event, water was applied up to 100% of field capacity (estimated at weight basis). The unit plot size was 18 square meter (3 m × 6 m). A processing potato variety, 'BARI Alu-25 (cv. 'Asterix') was used in this study.

Seed potatoes were planted on 29 November in 2020, with the row to row spacing of 60 cm and plant to plant 15 cm. After planting of potato, 20 mm of irrigation water was applied in every furrow in all treatments for ensuring proper germination and the irrigation treatments were initiated after plant establishment. The recommended doses of fertilizers were nitrogen (N) at 120, phosphorus (P) at 30, potassium (K) at 100, sulfur (S) at 15, zinc (Zn) at 4, and boron (B) at 1.4 kg $ha^{-1}$ and applied in the form of urea, triple super phosphate, muriate of potash, gypsum, zinc sulfate and borax, respectively (FRG, 2018). Decomposed cowdung was applied @ 4 t $ha^{-1}$ before land preparation. Some of fertilizers were applied as basal during land preparation 4 days before planting. Remaining were applied as side-dressing during earthing up operation followed by irrigation. In the second season, potatoes were first planted on 27 November 2021 maintaining the same cultural practices. But heavy rainfall (364 mm) in five consecutive days created water logged condition in the field and crops were totally damaged. Then replanting of potato was done on 16 December 2021. Fertilizer application and other cultural practices were same as the first season. Adequate plant protection measures were taken whenever required. In order to assess the change in soil water status, soil moisture was measured periodically by gravimetric method in 0–15, 15–30 and 30–45 cm soil profiles, considering the effective root zone of potato as 45 cm. The soils were sampled from both the center of the raised beds and bottom of the furrows with the depth of 15 cm increment during the time of planting to harvest. The calculated amount of irrigation water was supplied to the experimental plot using a polyethene hose pipe connected to a water flow meter. Seasonal crop water use (CWU) and the change in soil water contribution before planting and final harvest was estimated by the soil water balance approach (Micheal 1978; Sarker et al., 2019; 2020). Three plants were randomly collected from each treatment periodically to record the data on dry matter partitioning of potato plants. The roots and tubers were collected, cleaned and washed on a nylon net with clean tap water. The dry matter of roots, stems, leaves and tubers were separated and dried in the oven at $60^0$ C until a constant weight was achieved and expressed in g $plant^{-1}$. Aside from dry matter content per plant, dry matter percentage of potato also determined after harvesting of potato. For this, two to three potatoes were collected from each of five places from the pile of harvested potatoes to make a representative sample of potatoes. Then the collected samples were divided into three each of 200 -250 g potatoes. Sample potatoes were weighed, sliced and dried in an oven to determine the dry matter percentage. At harvest on 28 February 2021, 10 plants were selected randomly from each plot to record data periodically on plant characters like plant height, stem per hill, number of tuber per hill, weight of tuber per hill and tuber yield. For determining dry weight of tubers, 500 grams of potatoes were sliced, dried in the sun for two days and then dried in oven at 65 $^oC$ for 72 h. Then the samples were cooled and weighed.

Crop water productivity (WP) was calculated as the ratio of tuber yield (t $ha^{-1}$) and crop water use, and expressed as kg $m^{-3}$. Data on tuber yield and yield attributes and dry matter of potato were statistically analyzed to test the effects of fertilizer and irrigation levels on these parameters using MSTAT-C program. All the treatment means were subjected to analysis of variance (ANOVA) and compared for any significant differences at $P < 0.05$.

## Results and Discussion

### *Fresh tuber yield of export and processing potato*

Yield contributing parameters and tuber yield of potato affected by different irrigation and fertilizer levels are presented in Table 1a and 1b. Neither of yield contributing parameters, nor the tuber yield were significantly affected by either the irrigation or the fertilizer treatments. But tuber yield was slightly increased in the irrigation treatment $I_2$, where last irrigation was applied at 75 days after planting up to 50% of field capacity. Similarly, fertilization treatment $F_2$ where SOP and vermicompost were applied produced the slightly higher yield than other treatments. A trivial difference in yield between irrigation levels $I_1$ and $I_3$ and also between the fertilizer treatments $F_1$ and $F_3$ were observed. Most of the yield contributing parameters like plant height, stem per plant, number of tuber per plant, weight of tuber per plant showed similar patterns in their variations. Yield differences were between the fertilizer treatments were very low in the second season than that in the first season. This may be due to fertilizer effects were minimized by the heavy rainfall that possibly washed out some portion of applied fertilizer after few days of planting. However, the interaction of fertilizer and irrigation also led to insignificant effect on both yield contributing parameters and tuber yield.  In 2020 – 2021, tuber yield ranged from 29.92 to 32.10 t/ha for $I_1$, from 31.14 to 34.71 t/ha for $I_2$ and from 31.51 to 32.47 t/ha for $I_3$ while in 2021 – 2022, it ranged from 22.52 to 24.04 t/ha for $I_1$, from 23.13 to 26.08 t/ha for $I_2$ and from 28.86 to 26.46 t/ha for $I_3$ with minimum vales in $F_1$ fertlizer level and maximum values in $F_2$ fertilizer levels. The better plant growth under $I_2$ irrigation treatment and $F_2$ fertilizer treatment produced slightly better tuber yield than other treatments.

Table- 1a. Tuber yield and yield contributing characters of processing potato (BARI Alu-25) under different irrigation and fertilizer levels during 2020 - 2021

| Treatment | Plant height (cm) | Stem/plant (no.) | Potato/plant (no.) | Tuber wt/plant (g) | Tuber yield (t/ha) |
|---|---|---|---|---|---|
| Irrigation levels | | | | | |
| $I_1$ | 54.22 | 4.04 | 7.70 | 317.51 | 30.80 |
| $I_2$ | 56.22 | 3.15 | 8.30 | 334.04 | 32.89 |
| $I_3$ | 55.04 | 3.19 | 7.26 | 320.08 | 31.74 |
| $LSD_{0.05}$ | ns | ns | ns | ns | ns |
| CV(%) | 9.15 | 6.29 | 7.16 | 10.06 | 8.24 |
| Fertilizer levels | | | | | |
| $F_1$ | 52.56 | 3.26 | 7.81 | 307.27 | 30.86 |
| $F_2$ | 59.22 | 3.85 | 8.41 | 335.56 | 33.09 |
| $F_3$ | 52.89 | 3.26 | 7.04 | 311.81 | 31.48 |
| $LSD_{0.05}$ | 5.82 | ns | ns | ns | ns |
| CV(%) | 8.11 | 6.78 | 7.48 | 11.26 | 9.02 |
| Irrigation x Fertilizer | | | | | |
| $I_1F_1$ | 52.67 | 3.44 | 7.78 | 299.21 | 29.92 |
| $I1F_2$ | 61.00 | 5.00 | 8.44 | 341.40 | 32.10 |
| $I1F_3$ | 51.00 | 3.67 | 6.89 | 314.91 | 30.37 |
| $I_2F_1$ | 53.67 | 3.11 | 7.67 | 322.96 | 31.14 |
| $I_2F_2$ | 58.00 | 3.44 | 9.22 | 360.96 | 34.71 |
| $I_2F_3$ | 52.33 | 3.33 | 6.56 | 322.98 | 31.62 |
| $I_3F_1$ | 52.33 | 3.22 | 8.00 | 310.63 | 31.51 |
| $I_3F_2$ | 56.67 | 3.11 | 7.56 | 324.31 | 32.47 |
| $I_3F_3$ | 53.33 | 2.78 | 7.67 | 320.54 | 32.44 |
| $LSD_{0.05}$ | ns | ns | ns | ns | ns |
| CV(%) | 8.11 | 6.78 | 7.48 | 11.26 | 9.02 |

Table- 1b. Tuber yield and yield contributing characters of processing potato (BARI Alu-25) under different irrigation and fertilizer levels during 2021 - 2022

| Treatment | Plant height (cm) | Stem/plant (no.) | Potato/plant (no.) | Tuber wt/plant (g) | Tuber yield (t/ha) |
|---|---|---|---|---|---|
| Irrigation levels | | | | | |
| $I_1$ | 59.07 | 3.30 | 8.04 | 233.02 | 23.12 |
| $I_2$ | 58.00 | 2.93 | 7.67 | 260.12 | 23.58 |
| $I_3$ | 53.63 | 3.19 | 7.96 | 206.08 | 23.49 |
| $LSD_{0.05}$ | ns | ns | ns | ns | ns |
| CV(%) | 7.23 | 6.62 | 5.79 | 8.45 | 4.34 |
| Fertilizer levels | | | | | |
| $F_1$ | 56.66 | 3.22 | 8.85 | 227.73 | 22.84 |
| $F_2$ | 59.29 | 2.74 | 7.04 | 227.83 | 23.82 |
| $F_3$ | 54.74 | 3.44 | 7.78 | 243.65 | 23.53 |
| $LSD_{0.05}$ | ns | ns | ns | ns | ns |
| CV(%) | 7.23 | 6.98 | 6.48 | 8.26 | 6.02 |
| Fertilizer levels | | | | | |
| $I_1F_1$ | 56.00 | 3.56 | 9.89 | 233.07 | 22.52 |
| $I1F_2$ | 65.22 | 2.89 | 7.67 | 248.81 | 24.04 |
| $I1F_3$ | 56.00 | 3.44 | 6.56 | 217.17 | 24.80 |
| $I_2F_1$ | 56.22 | 2.89 | 8.44 | 238.30 | 23.13 |
| $I_2F_2$ | 58.00 | 2.56 | 6.22 | 250.48 | 26.08 |
| $I_2F_3$ | 59.77 | 3.33 | 8.33 | 291.58 | 25.53 |
| $I_3F_1$ | 57.78 | 3.22 | 8.22 | 211.82 | 22.86 |
| $I_3F_2$ | 54.66 | 2.78 | 7.22 | 184.20 | 26.46 |
| $I_3F_3$ | 48.44 | 3.56 | 8.44 | 222.21 | 25.15 |
| $LSD_{0.05}$ | ns | ns | ns | ns | ns |
| CV(%) | 7.23 | 6.98 | 6.48 | 8.26 | 6.02 |

***Total dry matter and dry matter partitioning of potato***

The total dry matter, TDM, of potato plants as influenced by different irrigation and fertilizer treatments recorded at different dates over the growing seasons showed that it increased slowly up to 45 DAP; thereafter it increased sharply (Fig. 1a and 1b). As far as crop growth stages are concerned, there was a big difference between early stages (at 45 and 65 DAP) and the differences were minimal at the later growth stages.  But no significant differences in total dry matter were found among irrigation treatments for a particular stage. Similarly, among the fertilizer treatments, differences in dry matter content were insignificant. Slightly higher TDM was observed in fertilizer treatment $F_2$ at all levels of irrigations. The increase in TDM under this fertilizer treatment might be due to the application of vermi-compost, an organic fertilizer, along with a potassium fertilizer, sulphate of potash (SOP). A study from Denmark demonstrates the higher dry matter content achieved with SOP (potassium sulphate) rather than MOP (potassium chloride). This is due to the chloride in the muriate of potash (MOP) having a negative effect on tuber dry matter content of potato.

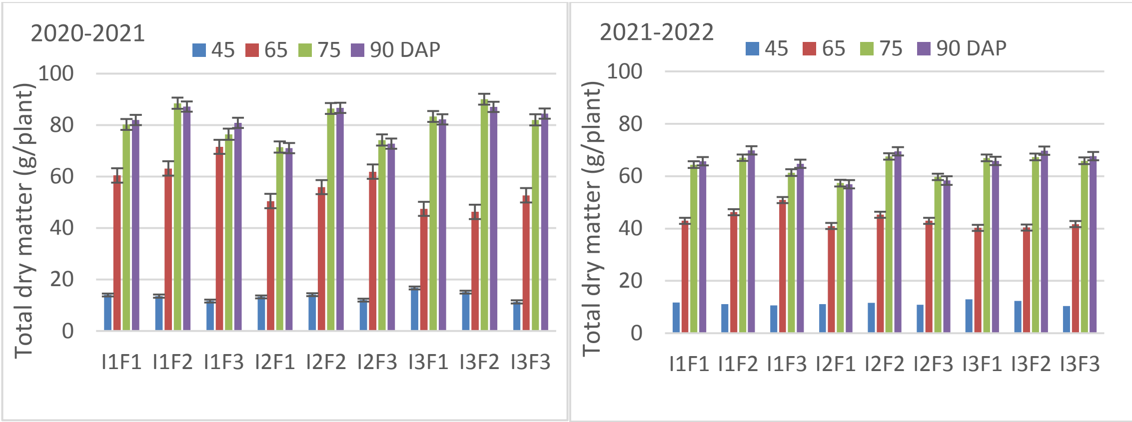



Figure 1 Effect of irrigation and fertilizer on total dry matter content at different growth stages (days after planting, DAP) of potato during 2020 – 2021 and 2021 – 2022.

The accumulation of dry matter in different parts (root, stem, leaves and tuber) of potato plants as influenced by irrigation and fertilizer treatments at different growth stages are depicted in Fig. 2a and 2b. There was no significant effect of irrigation on dry matter partitioning in root, stem, leaves and tuber of potato. The fertilizer treatment also led to an insignificant effect on dry matter partitioning in different organs in potato plant.


Fig. 2a: Dry matter allocation of potato plant at different growth stages under different irrigation and fertilizer managements during crop growing season 2020 - 2021

At the early stage (45 DAP), the share of the leaves was greater than that of the stem, root and tuber thereafter, it decreased, and the share of stems started to increase as the plant grew up. At maturity (90 DAP), the contribution of the share of tuber to the dry matter per plant was greater than the share of stem and leaves. This was due to mobilization of assimilates from leaves and stem to the tuber for bulking. The share of stem was also higher than that of root and tuber at early stage when only vegetative growth happened. At the later stage, tuber formation starts and thereby increased its contribution to the total dry matter content. Tuber dry matter was somewhat affected by fertilizer with higher values in $F_2$ than $F_1$ and $F_3$ under all irrigation treatments. The contribution of tuber to dry matter was found to increase from tuber development at mid stage and reached its maximum at maturity stage.


Fig. 2b: Dry matter allocation of potato plant at different growth stages under different irrigation and fertilizer managements during crop growing season 2021 - 2022

## Dry matter percentage and dry matter yield of potato

Tuber dry matter percentage was not affected by the irrigation schedule, but it was affected significantly by fertilizer treatments in the first year but insignificantly in the second year with maximum value (21.55% in first season and 19.96% in the second season) obtained from $F_2$ where both SOP and vermicompost were used (Fig. 3a and 3b). The second highest value was obtained from fertilizer treatment $F_3$, where only SOP with recommended fertilizers were used, percentage of dry matter retained in tuber was in between that

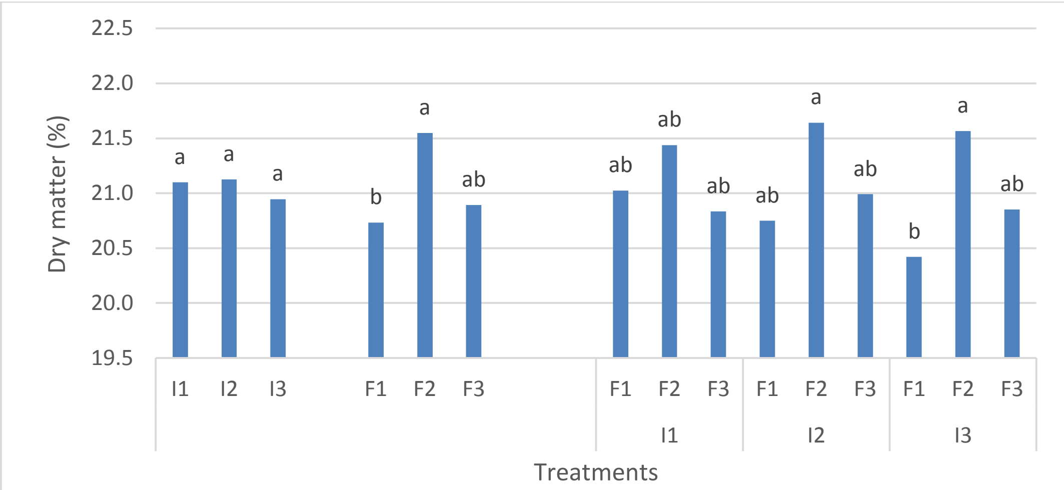



Fig. 3a. Dry matter percentage of potato tuber as influenced by different fertilizer and irrigation managements in 2020 – 2021 season

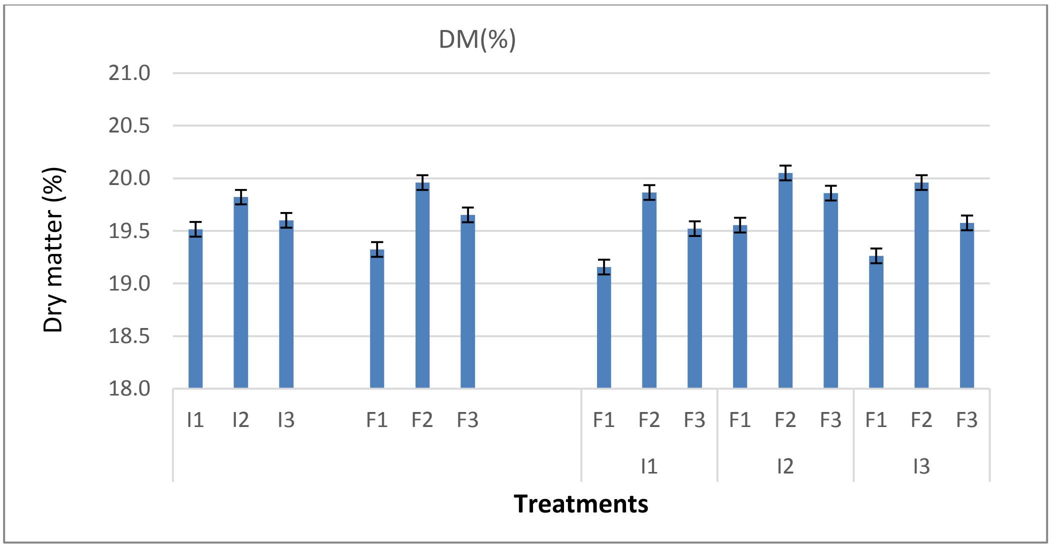



Fig. 3b. Dry matter percentage of potato tuber as influenced by different fertilizer and irrigation managements in 2021 – 2022 season

retained under fertilizer treatments $F_1$ and $F_2$. Obviously, the lowest value of dry matter percentage (20.73% in the first and 19.32% in the second season) was obtained from recommended fertilizer dose. But in the following year, both dry matter percentage and dry matter yield were found lower due to late replanting. Combination of irrigation and fertilizer had almost similar effect on accumulation of dry matter in tuber as realized by irrigation and fertilizer separately. Here, the highest dry matter (21.65% in first and 20.05% in the second season) retained in $F_2$ under $I_2$ irrigation treatment insignificantly followed by $I_3F_2$ (21.57% in first and 19.86% in the second season) and all other combinations, except the lowest percentage (20.42% in the first and 19.16% in the second season) retained in $F_1$ under $I_3$ irrigation treatment ($I_3F_1$). Though variation in dry matter percentage was not significant among irrigation treatments, treatment $F_2$ under all irrigation treatments contributed to the higher dry matter percentage than both $F_1$ and $F_3$. A significant and positive effect of vermicompost on dry matter accumulation in potato tuber was reported by Ferdous et al. 2019. Kahlel (2015) also noted the highest percentage of dry matter in tubers resulted from the treatment of organic fertilization by irrigation. Dry matter yield of potato depends on both tuber yield and dry matter percentage as the yield of dry matter is a product of the

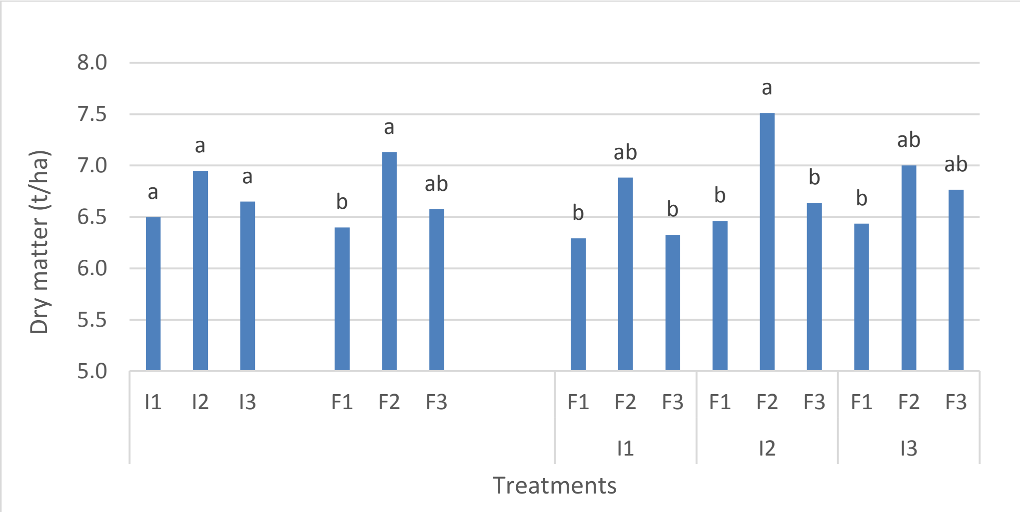



Fig. 4a. Dry matter yield of potato as influenced by different fertilizer and irrigation treatments in 2020 – 2021 season

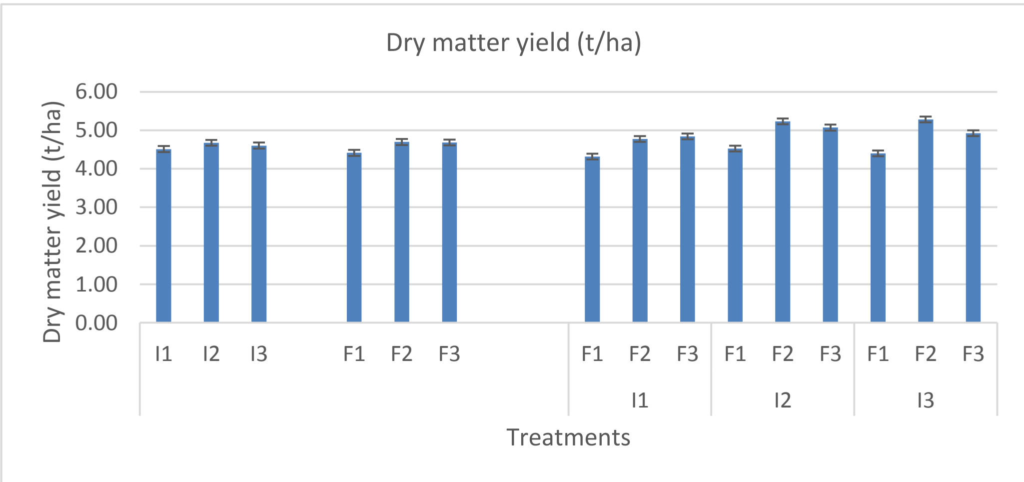
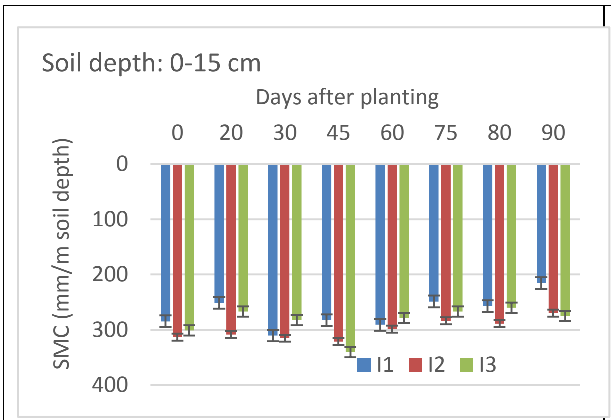


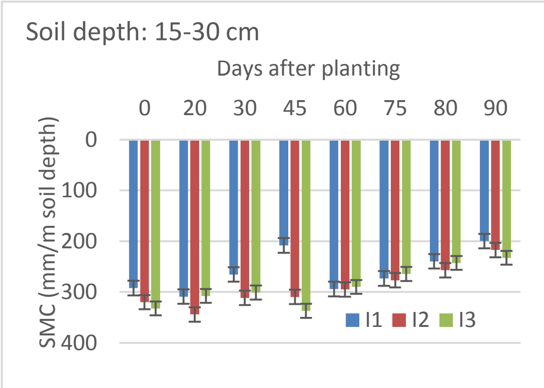

Fig. 4b. Dry matter yield of potato as influenced by different fertilizer and irrigation treatments in 2021 – 2022 season

fresh yield of tubers and the content of dry matter in tubers. According to Gabriel and Świeżyński (1977), the value of dry matter yield is determined in 72-92% by the yield of tubers, and only in 14-15% by the content of this trait in tubers. So, dry matter yield of potato followed the similar trend as that of dry matter percentage and fresh tuber yield (Fig. 4a and 4b). In this case, dry matter yield was found the lowest (6.29 t/ha) in $F_1$ under $I_1$ irrigation treatment and that of the highest (7.51 t/ha) obtained in $F_2$ under $I_2$ irrigation treatment in the first season while dry matter yield was varied from the lowest 4.23 t/ha to the highest of 5.11 t/ha, respectively, in the second season.

## Soil water content, crop water use and water productivity

Soil water content at different layer was measured periodically and before each irrigation gravimetrically and demonstrated in Fig.3. Irrespective of irrigation treatments, soil water content varied with soil depth with lower in top 0-15 cm layer and higher in mid-and bottom layer as depletion of soil moisture was more in top layer. In this layer, soil water was progressively decreased with advancement of crop stages. When the top layer became dry, the mid layer was the primary source of water used by the plant, due either to upward movement of water, or by direct



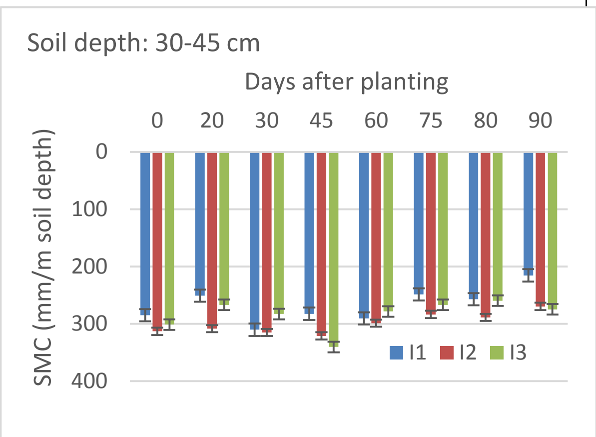
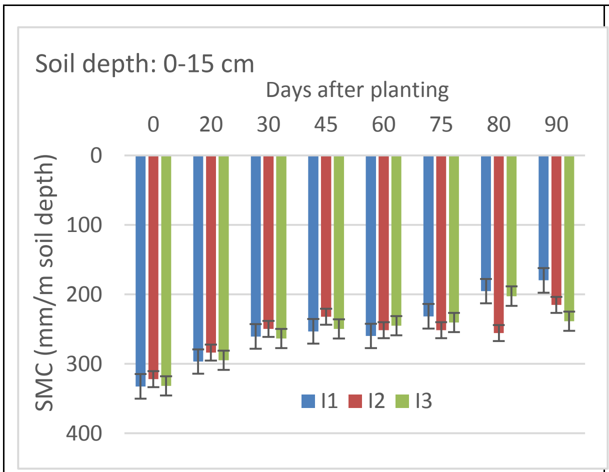
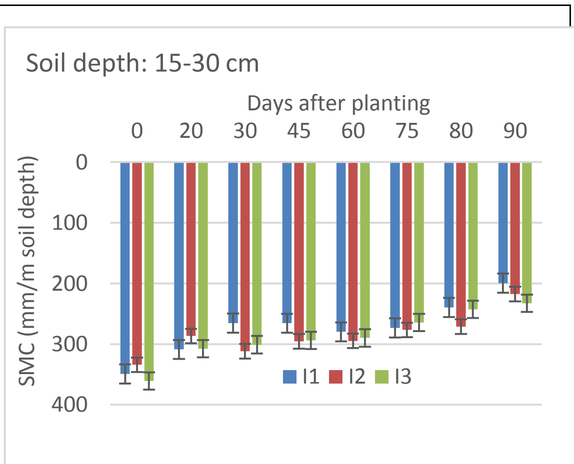




Figure 3a. Profile soil moisture (SMC) under different irrigation levels during growing season of potato in 2020 – 2021. Vertical bars indicate the standrad error.

Figure 3. Profile soil moisture (SMC) under different irrigation levels during growing season of potato. Vertical bars indicate the standrad error.



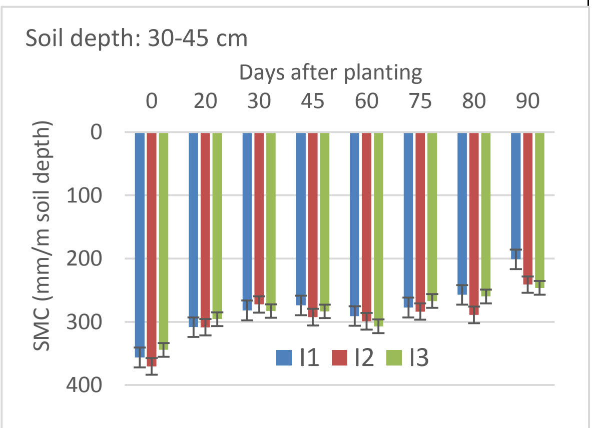




Figure 3b. Profile soil moisture (SMC) under different irrigation levels during growing season of potato in 2021 - 2022. Vertical bars indicate the standrad error.

water uptake by the roots within this depth. Thus, the pattern of changes in soil water in mid layer (15-30 cm) was almost same as of top layer. In the bottom layer (30-45 cm), changes in soil water with advancement of time were marginal due to less water uptake by potato plants and no or little evaporation took place from this layer. As treatment $I_2$ and $I_3$ received irrigation at 75 and 80 DAP, respectively, water content was found higher at the end of crop duration in all layers.

Crop water use was equal to the applied irrigation water, effective rainfall plus contribution by soil water during the growing season. Water use by the crop varied with the variation in amount of water applied to the crop and ranged from 252 to 271 mm in the first season and 256 to 279 mm with minimum in $I_1$ treatment and maximum in $I_3$ (Table 2a and 2b). Though CWU was same across all fertilizer treatments under a particular irrigation treatment, WPs were varied due to difference in tuber yields. WPs ranged from 11.87 to 12.74 kg/m3 for $I_1$, from 11.66 to 13.0 kg/m3 for $I_2$, and 11.63 to 11.98 kg/m3 for $I_3$ with minimum values in $F_1$ and maximum values in $F_2$ in the first year. In the following year, WPs ranged from 8.80 to 9.69, 8.35 to 9.41 and 8.19 to 9.48 kg/m3 for I1, I2 and I3, respectively.

Table 2a: Irrigation water applied, crop water use (CWU) and water productivity (WP) of potato cultivated under three irrigation and fertilizer levels

| Irrigation level | Fertilizer level | IR (mm) | SWC (mm) | ER (mm) | CWU (mm) | Tuber yield (t/ha) | WP (kg/m3) |
|---|---|---|---|---|---|---|---|

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| $I_1$ | $F_1$ | 196 | 56 | 0 | 252 | 29.92 | 11.87 |
| | $F_2$ | 196 | 56 | 0 | 252 | 32.10 | 12.74 |
| | $F_3$ | 196 | 56 | 0 | 252 | 30.37 | 12.05 |
| $I_2$ | $F_1$ | 225 | 42 | 0 | 267 | 31.14 | 11.66 |
| | $F_2$ | 225 | 42 | 0 | 267 | 34.71 | 13.00 |
| | $F_3$ | 225 | 42 | 0 | 267 | 31.62 | 11.84 |
| $I_3$ | $F_1$ | 232 | 39 | 0 | 271 | 31.51 | 11.63 |
| | $F_2$ | 232 | 39 | 0 | 271 | 32.47 | 11.98 |
| | $F_3$ | 232 | 39 | 0 | 271 | 32.44 | 11.97 |

Table 2b: Irrigation water applied, crop water use (CWU) and water productivity (WP) of potato cultivated under three irrigation and fertilizer levels

| Irrigation level | Fertilizer level | IR (mm) | SWC (mm) | ER (mm) | CWU (mm) | Tuber yield (t/ha) | WP (kg/m3) |
|---|---|---|---|---|---|---|---|
| $I_1$ | $F_1$ | 162 | 58 | 36 | 256 | 22.52 | 8.80 |
| | $F_2$ | 162 | 58 | 36 | 256 | 24.04 | 9.39 |
| | $F_3$ | 162 | 58 | 36 | 256 | 24.80 | 9.69 |
| $I_2$ | $F_1$ | 197 | 44 | 36 | 277 | 23.13 | 8.35 |
| | $F_2$ | 197 | 44 | 36 | 277 | 26.08 | 9.41 |
| | $F_3$ | 197 | 44 | 36 | 277 | 25.53 | 9.22 |
| $I_3$ | $F_1$ | 204 | 39 | 36 | 279 | 22.86 | 8.19 |
| | $F_2$ | 204 | 39 | 36 | 279 | 26.46 | 9.48 |
| | $F_3$ | 204 | 39 | 36 | 279 | 25.15 | 9.02 |

WPs obtained in this study were consistent to other studies (Sarker et al., 2019; Jovanovic et al., 2010; Ahmadi et al., 2010). The results indicate that $I_2$ irrigation strategy produced the greater WP as compared to $I_1$ and $I_3$. The combination of $F_2$ and $I_2$ produced the highest tuber yield that resulted in the highest WP. The reduced WP in $I_1$ and $I_3$ is mainly due to lower fresh tuber yield compared to water use by the crop. This study revealed that proper fertilizer and irrigation strategy could improve water productivity of potato.

## Conclusion

Total dry matter and yield of potato were influenced slightly by the combination of fertilizer and irrigation strategies. Fertilizer treatment with SOP and vermicompost ($F_2$) produced the higher tuber yield and dry matter percentage under all levels of irrigation. Irrigation treatments had insignificant effect on increasing dry matter percentage, though trivially higher dry matter percentage was recorded in $I_2$ irrigation strategy. Thus, the combination of fertilizer treatment $F_2$ and irrigation treatment $I_2$ demonstrated to be the best to increase dry matter, tuber yield and water productivity and may be preferred for growing export and processing potato in Bangladesh. Fertilizer treatment with 50% SOP ($F_3$) resulted insignificant effect on tuber yield and dry matter content. This study needs to be repeated to understand the fertilizer levels with various irrigation strategies for improving the dry matter, tuber size, yield, water productivity and tuber quality for production of export quality potato which will benefit the growers to have higher price.

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# EFFECT OF SALINE WATER IRRIGATION WITH DIFFERENT DOSES OF POTASSIUM ON CROP GROWTH AND YIELD OF MUNGBEAN

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## Abstract

The experiment was conducted at the shade house of IWM Division, BARI, Gazipur during 2018 - 2019 to evaluate the effect of saline water irrigation with different doses of potassium on crop growth and yield of mung bean. The treatments comprised different combinations of three salinity levels (4 dS/m, 8 dS/m and 12 dS/m) with four potassium levels (0%, 100%, 125% and 150% of recommended dose). Results of experimental findings revealed that salinity seriously affected yield and yield contributing characters of mung bean and potassium can eliminate such type of deleterious effects of salinity to some extent. Application of higher amount of K improved the plant fresh weight and dry weight, and chlorophyll content. Application of different levels of potassium did not influence on plant height, number of leaves and root length. However, different levels of potassium application increased the uptake of Ca, Mg, P and K, while decreased Na uptake several fold. Mg accumulation was unchanged due to salinity. It was concluded that application of higher levels (125% or 150% of recommended dose) of K improves growth and yield of mung bean under saline conditions.

## Introduction

Climate change is now one of the biggest problems across the globe as its impacts on human being and the environment are very terrible and prolonged. Bangladesh is exposed to be one of the most vulnerable countries of the world to climate change and sea level rise. There are several environmental issues and problems that are hindering the development of Bangladesh. Salinity is such an environmental problem. Salinity has been a threat to agriculture in some parts of the world for over 3000 years; in recent times, the threat has grown (Tim Flowers, 2006). It is estimated that at least 20% of all irrigated lands are salt affected (Pitman and Läuchli, 2002) in whole world and about 53% of the coastal areas are affected by salinity in Bangladesh (Haque, 2006). Agricultural land use in these areas is very poor, which is much lower than country's average cropping intensity. Salinity causes unfavorable environment and hydrological situation that restrict the normal crop production throughout the year. Excessive soil salinity may adversely affect plant growth by increasing the osmotic pressure in the solution, forming toxicity in the plant tissue and changing the plants mineral nutritional characteristics (Michael, 1978). In the face of high salinity, a plant’s ability to control water potential and hydraulic conductivity is essential for the maintenance of water levels in tissue (Negrao et al., 2017).

Among the alternatives employed to minimize the deleterious effects caused by the high salt concentrations on plants, K fertilization stands out. Hence, studies have associated the tolerance of crops to salinity with an adequate K nutrition (Blanco et al., 2008; Gurgel et al., 2010). Potassium is essential to plants because it plays a key role in osmotic regulation and promotes the maintenance of turgor in guard cells. By increasing their osmotic potential, potassium allows this cell to absorb more water, and the adjacent cell acts as a counter cation for anion accumulation and electro genic transport processes and, consequently, generates higher turgor pressure (Langer et al., 2004; Islam et al., 2015).

Besides being an osmoregulator, K creates an osmotic gradient that allows water movement and regulates stomatal opening and closure, playing an essential role in water saving and cell turgor,transport of carbohydrates and respiration (Shimazaki et al., 2007). Application of higher

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levelof K improves growth and yield of mungbean under mild level of saline conditions (M. E. Kbir et al.,2004).

The mungbean (*Vigna radiata*), locally known as the *moog, sonamoog*, is a plant *species* in the legume family. It has a distinct advantage of being short-duration and can grow in wide range of soils and environments (as mono or relay legume). It has a high nutrient value with protein, carbohydrate, minerals, pro vitamin A and vitamin B-complex.

## Material and Methods

An experiment was conducted at IWM shed house of Bangladesh Agricultural Research Institute, Gazipur. BARI Mungbean -5 is used for the experiment. The experimental design was in CRD, with four replicates, and the treatments consisted of four levels of irrigation water electrical conductivity - ECw (0, 4, 8 and 12 dS/m) and four K doses (0, 100, 125 and 150% of recommendation). The treatments were

$T_1$= Irrigation with fresh water with 100% potassium

$T_2$= Irrigation with (4 dS/m) saline water with 0% potassium

$T_3$= Irrigation with (4 dS/m) saline water with 100% potassium

$T_4$= Irrigation with (4 dS/m) saline water with 125% potassium

$T_5$= Irrigation with (4 dS/m) saline water with 150% potassium

$T_6$= Irrigation with (8 dS/m) saline water with 0% potassium

$T_7$= Irrigation with (8 dS/m) saline water with 100% potassium

$T_8$= Irrigation with (8 dS/m) saline water with 125% potassium

$T_9$= Irrigation with (8 dS/m) saline water with 150% potassium

$T_{10}$= Irrigation with (12 dS/m) saline water with 0% potassium

$T_{11}$= Irrigation with (12 dS/m) saline water with 100% potassium

$T_{12}$= Irrigation with (12 dS/m) saline water with 125% potassium

$T_{13}$= Irrigation with (12 dS/m) saline water with 150% potassium

Total fifty-two plastic pots (depth: 34 cm and diameter on an average 30.50 cm) were used. Each pot was filled with 24 kg soil collected from IWM experiment field and contained two plants. The bottom of the pot was perforated and filled with the coarse aggregate to drain the excess of water to a plate, in order to analyzed their chemical composition. Direct soil EC meter was used to measure in situ soil salinity. The salinity data were measured at two depths (0-5 cm) and (5-15 cm) for each treatment. Four levels of K in the form of muriate of potash (MOP) were applied as the potassium source. Recommended dose of fertilizer was applied equally to all treatments.

The irrigation waters with the respective ECw values were prepared artificially by mixing raw salt into water using trial and error method in the laboratory to get the expected soil salinity. Before using raw salt, salt analysis was done by Flame photometer to compare the amount of percentage of each component (e.g. Na, K, Ca) of salt with the sea salt, and found that raw salt contains desired amount of NaCl as in sea salt.

Before sowing, equal amount of saline water irrigation was used for developing and maintaining soil salinity to some extent in the pots of different treatments. Pre-soaked purified 10 seeds were sown in each pot on 22 March, 2018 and irrigated with fresh water for easy germination. At the 2nd trifoliate leaf stage, two uniform and healthy plants were kept at each pot and other plants were picked out. Fresh water was used for plant establishment up to 2nd trifoliate leaf appeared before applying actual treatments. When the first trifoliate appeared, all the treatments were started and continued till maturity. Soil salinity was measured after each irrigation for different treatments.

Amount of irrigation water was applied up to field capacity. Plants were grown up to maturity stage and dry matter yield was recorded. Extra 1 replication was included for growth stage wise sampling.

Owing to implement 2nd year study, the seeds were sown as same procedure of previous year on 20 March, 2021. But, germination was failed and once more seeds were sown on 30, March. 2022. Though, germination was perfect, but growth of the plant was not so good and ultimately they were not sustained in the end.

Table- 1. Physical and chemical characteristics of the primary soil

| Soil | Texture | pH | Organic Material (%) | Ca | Mg | K | Total N (%) | P | S |
|---|---|---|---|---|---|---|---|---|---|
| | | | | meq/100ml | | | | µg/ml | |
| Studied soil | silty clay loam | 6.4 | 1.39 | 5.2 | 1.8 | 0.12 | 0.074 | 39.0 | 19.0 |

## Results and Discussion

### *Yield and yield components of mungbean*

The summary of ANOVA suggested that EC of irrigation waters significantly ($p<0.05$) affected yield and all the other yield components (Table 1) of mungbean. There was significant difference in the relative yield decrease with salinity increase between the lowest and highest K application rates. The mungbean yield decreased to 0.89 and 1.29 t ha-1, respectively with saline irrigation and variable level of potassium doses when compared to 1.47 t ha-1 in pots treated with non-saline irrigation water with recommended potassium dose. The highest yield (1.47 t ha-1) was obtained at treatment $T_1$ (irrigation with fresh water with 100% potassium) and the lowest yield of 0.89 t ha-1 was recorded at treatment $T_{10}$ (irrigation with (12 dS/m) saline water with 0% potassium) (Table 1). Table 1. revealed that the highest yield (1.29 t/ha and 1.28 t/ha) among the saline irrigation treatments was achieved with the treatment ($T_5$) (Irrigation with 4 dS/m saline water with 150% potassium) and treatment ($T_3$) (irrigation with 4 dS/m saline water with 100% potassium) which was significantly comparable with the treatment ($T_4$) (Irrigation with 4 dS/m saline water with 125% potassium), treatment ($T_9$) (Irrigation with (8 dS/m) saline water with 150% potassium). M. Salim and M. G. Pitman showed 60 % and 25% reduction of mungbean yield due to addition of 50 mM NaCl and 100 mM NaCl respectively. But in this study, maximum and minimum yield reduction due to 50 mM NaCl and 90 mM NaCl addition was 40 % and 12 % respectively. These result showed that the harmful effects of salinity on the yield of mungbean were minimized to some extent with potassium fertilization.

The ECiw x K interaction was significant ($p>0.05$) for all the yield parameters such as number of pod/plant, wt. of seeds/pod, 1000 seed wt. (gm), except pod length and no. of seeds per pod. All the yield parameters decreased with increasing salinity levels, but increased with the increasing potassium level. The highest no. of pods/plant (14.75), pod length (7.54 cm), no. of seeds/pod (9.71), wt. of seeds/pod (0.52 gm), 1000 seed wt. (55.27 gm) was achieved from the fresh water treatment. Among the saline water irrigation treatments, the treatment $T_3$ (irrigation with (4 dS/m) saline water with 100% potassium) and treatment $T_8$ (irrigation with (8 dS/m) saline water with 125% potassium) exhibited better performance for no. of pod/plant (12.00). The highest pod length (9.50 cm) was recorded for treatment $T_3$ along with treatment $T_6$. While the highest no. of seeds/pod was obtained for the treatment ($T_2$) irrigation with (4 dS/m) saline water with 0% potassium) along with treatment ($T_5$) irrigation with (4 dS/m) saline water with 150% potassium) (9.50). Whereas, the highest wt. of seeds/pod (0.49 gm), 1000 seeds wt. (50.79 gm) and seed yield (15.50 gm) was resulted from treatment $T_5$. However, the lowest no. of pod/plant (09.75), pod length (6.09 cm), wt. of seeds/pod (0.37 gm) and seed yield (8.89gm) was determined in treatment ($T_{10}$) (irrigation with (12 dS/m) saline water with 0% potassium). Treatment ($T_{10}$) and treatment ($T_{11}$) were significantly par with each other for the lowest wt. of seeds/pod and 1000 seed wt. The lowest no. of seeds/pod (8.46) was resulted from treatment $T_{12}$.

Table 2. Summary of analysis of variance (ANOVA) for yield and yield components of mungbean as affected by the application of saline water and potassium

| Treatments | Number of pod/plant | Pod length(cm) | Number of seeds/pod | Wt. of seeds/pod | 1000 seed wt. (gm) | Seed yield (gm/plant) |
|---|---|---|---|---|---|---|
| $T_1$ | 14.75 | 7.54 | 9.71 | 0.52 | 55.27 | 5.82 |
| $T_2$ | 10.75 | 7.42 | 9.50 | 0.42 | 47.05 | 4.38 |
| $T_3$ | 12 | 7.46 | 9.34 | 0.46 | 48.85 | 5.07 |
| $T_4$ | 10.75 | 7.40 | 9.38 | 0.47 | 48.51 | 5.04 |
| $T_5$ | 11.50 | 7.00 | 9.50 | 0.49 | 50.79 | 5.17 |
| $T_6$ | 11.25 | 7.46 | 9.33 | 0.43 | 43.37 | 4.36 |
| $T_7$ | 10.50 | 7.38 | 9.29 | 0.43 | 45.40 | 4.57 |
| $T_8$ | 12.00 | 7.44 | 9.25 | 0.45 | 45.46 | 4.73 |
| $T_9$ | 11.00 | 7.06 | 9.33 | 0.44 | 46.00 | 4.86 |
| $T_{10}$ | 9.75 | 6.09 | 8.84 | 0.37 | 39.38 | 2.96 |
| $T_{11}$ | 10.00 | 6.86 | 9.29 | 0.38 | 39.21 | 3.30 |
| $T_{12}$ | 10.25 | 6.96 | 8.46 | 0.40 | 40.21 | 3.56 |
| $T_{13}$ | 10.25 | 6.88 | 9.33 | 0.39 | 40.75 | 3.66 |
| CV(0.05) | 10.85 | 8.38 | 7.76 | 9.69 | 6.16 | 5.40 |
| LSD | 1.73 | 0.86 | 1.03 | 0.06 | 4.04 | 0.09 |

***Mungbean growth parameters at harvesting stage as affected by the application of saline water and potassium***

Plant height, root length, number of leaves, fresh and dry weight of different parts of mungbean were significantly affected by different salinity level (fig:1,2,3 and 4). Potassium can slightly reduce the hazardous effect of salinity on fresh and dry weight of different parts of mungbean. In presence of 150% K application, the fresh and dry weight of mungbean increased significantly for all salinity treatments.

Fig: 1. a. reveals that Salinity affected plant height of mungbean. The plant height decreased with the increase in salinity levels. However, there was no effect of K on plant height. Relative (per cent of control) plant height decreased ranged from 8% to 17% at 4 dS/m salinity level with all potassium doses except 100% potassium application. At 100% potassium with 4 dS/m salinity, there was a plant height increment of about 3.95%. Whereas, at 8 dS/m and 12 dS/m salinity level with all potassium doses, the plant height decreased ranged from 15% to 36% and 34% to 43% respectively. The minimum relative plant height (43%) was obtained at the highest salinity (S2) with no potassium fertilizer.

There was a significant positive plant fresh weight and dry weight response to K application. The plant fresh and dry weights reduction for zero K treatment with increasing salinity became significant (fig: 1. b & c). The fig. showed that the average decrease in plant FW and DW caused by an increase in salinity from 0 to 4 dS/m was approximately 4-42%. As the salinity increases further to 8 dS/m, a further weight reduction of approximately 12-51% for FW and 15-40% for DW, and the reduction continued to increase from 42-53% for FW and 43-61% for DW as the salinity increased from 8 to 12 dS/m. Comparing among the three salinity levels, it was showed for plant FW and DW that 125% potassium application treatments did better performance than 150% K application treatments.

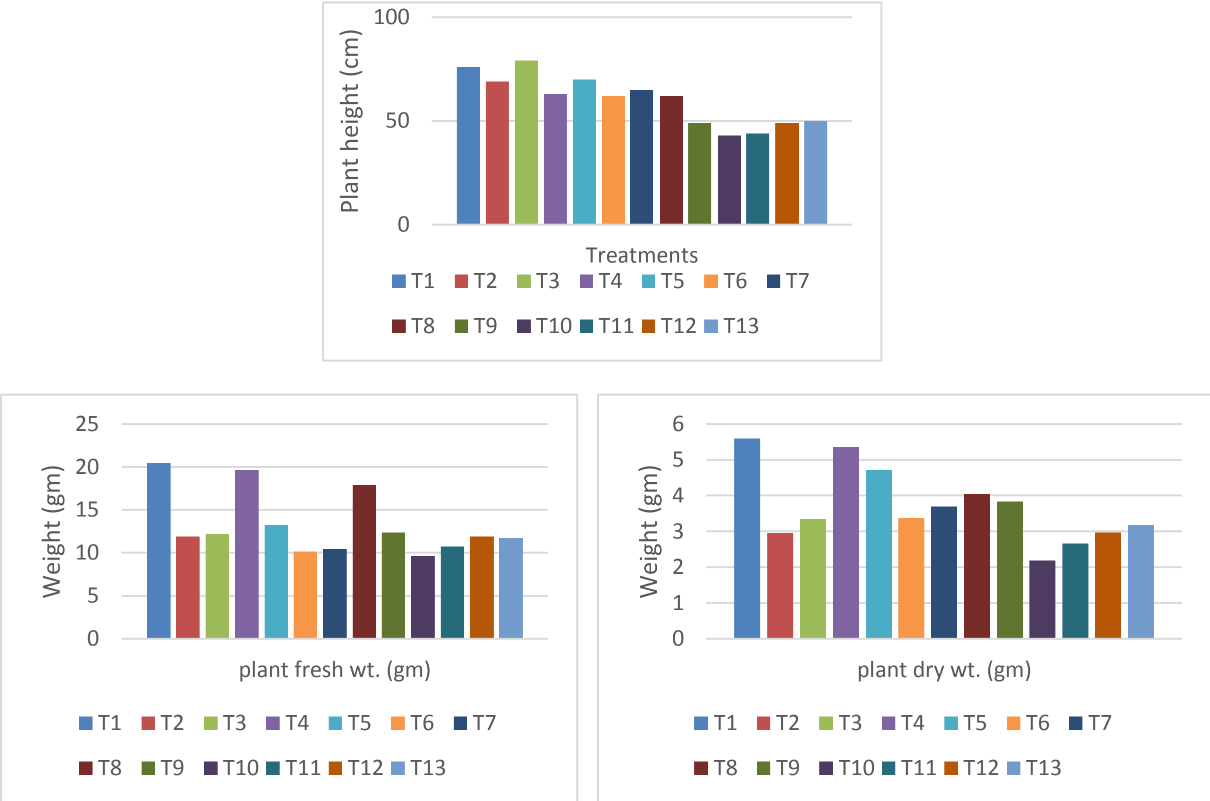


Fig. 1. Effect of salinity and potassium on plant height, plant FW and plant DW at harvesting stage of mungbean.

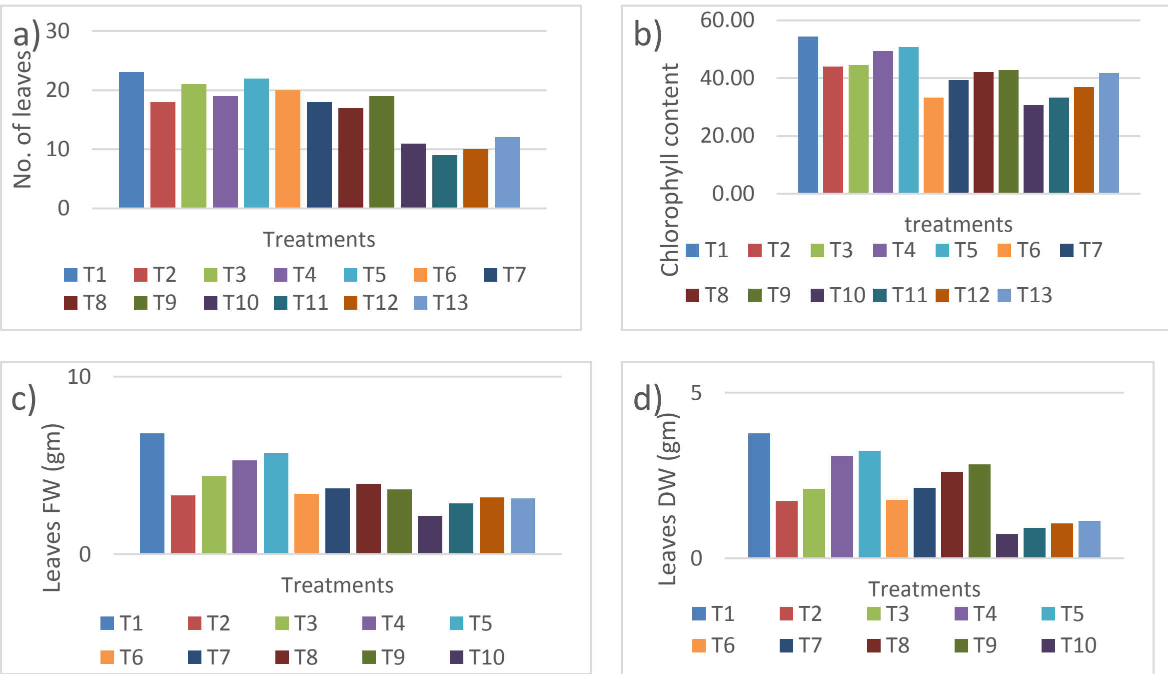


Fig. 2. Effect of salinity and potassium on number of leaves, leaves fresh weight and dry weight at harvesting stage of mungbean.

The results for number of leaves, leaves fresh weight (FW) and dry weight (DW) are given in fig: 2. (a, b, c) and pod fresh weight (FW) and dry weight (DW) are given in fig: 3 (a, b). These parameters were affected by salinity and potassium except number of leaves. No. of leaves did not show any response to potassium fertilizer levels. It was not also affected by low to mild salinity, but at 12 dS/m salinity it decreased markedly. Chlorophyll content at harvesting stage was affected by salinity and potassium (fig: (2.b)). With the increasing level of salinity chlorophyll content was decreased and decreasing level of K chlorophyll content was also decreased Therefore, the percent reduction in chlorophyll content due to salinity was range from 7-18 % in 4 dS/m level of the salinity, 21-39 % in 8 dS/m level of the salinity and 23-43 % in 12 dS/m level of the salinity. The fig: (2.c, d) showed that leaves FW and DW were already reduced at 4 dS/m salinity level and the reduction continued to increase as the salinity increased from 4 to 12 dS/m. The average decrease in leaves FW and DW at 4 dS/m salinity level was approximately 16-51% for FW and 14-54% for DW, at 8 dS/m salinity level was 42-50% for FW and 25-53% for DW and at 12 dS/m salinity level it was 53-68% for FW and 70-81% DW. Leaf chlorosis was observed in plant treated with 12 dS/m salinity. The effect of combination treatments of 12 dS/m salinity with 150 % of disappeared leaf chlorosis in comparison to that treated with saline water with 0%, 100% or 125% of K.

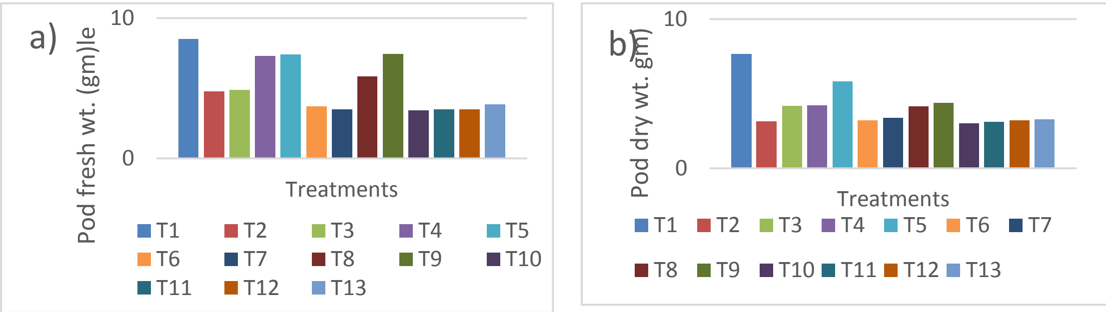


Fig. 3. Effect of salinity and potassium on pod fresh weight and dry weight at harvesting stage of mungbean.

Comparing control plants, pods fresh weight and dry weight reductions in 4 dS/m salinity was 13-44% and 24-60%, in 8 dS/m salinity was 13-60% and 43-58% and in 12 dS/m salinity was 55-60% and 58-61% respectively.

At each salinity level, leaves FW and DW and pods fresh weight and dry weight reduction was decreased as the application of K was increased. Therefore, application of higher level of potassium treatments increased FW and DW of leaves and pods of mungbean. However, the percent reduction in FW and DW of leaves and pods due to salinity was more in 0% K application treatments than others K application treatments.

Fig: 4 shows that Salinity levels, strongly affected the root length, root FW and root DW, and these parameters decreased linearly with increasing salinity levels. Potassium fertilizer levels did not have any effect on root length. Potassium application significantly affected dry and fresh weights of roots for any salinity level with different K doses. There was a significant positive fresh weight and dry weight response to K application. Root FW and DW were reduced with different levels of salinity under different potassium treatments compared to the control. Whereas, application of 150% of K increased the production of relative root fresh weight and dry weight (DW) at every salinity levels compared to the control. At 4 dS/m salinity the relative root FW and DW in ranged from 10 to 55% and 28 -76%, at 8 dS/m salinity from 34-68% and 36-80% and at 12 dS/m salinity from 70-80% and 67-83% respectively. Therefore, the percent reduction in root FW and DW due to salinity was more in 12 dS/m levels of the salinity treatments than others. However, application of increasing rate of potassium increased relative root FW and DW in all salinity levels. And this increasing rate was more in 150% K application treatments than others.

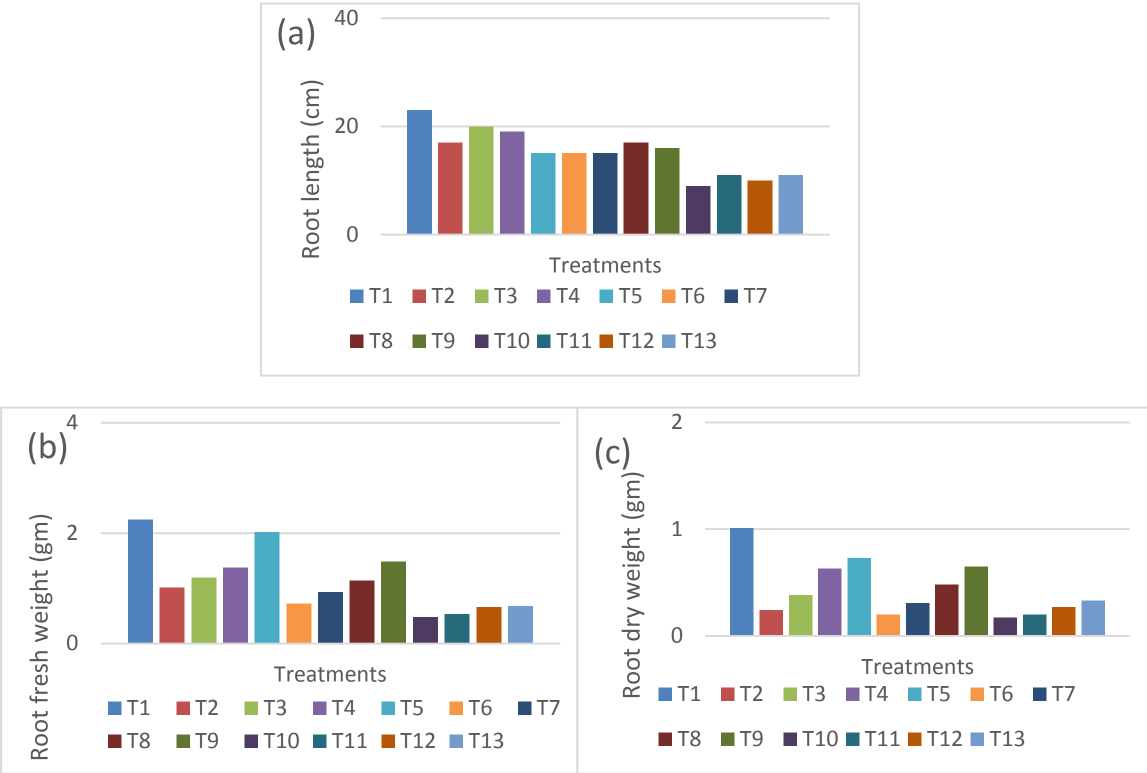


Fig. 4. Effect of salinity and potassium on root height, root FW and root DW at harvesting stage of mungbean.

Saline irrigation significantly ($P<0.001$) decreased mungbean yield. plant height, root length, number of leaves and all fresh and dry weight of different parts of mungbean as compared to control. The K addition improved almost all the parameters except plant height, root length and number of leaves. It has been previously reported that increased soil salinity resulted in reduction of plant growth, yield and in severe case, total crop failure (Qadir et al., 2000). In saline soils, water uptake by roots was limited because of higher osmotic potential which increased Na and Cl toxicity and thus plant production was affected in salt-affected soils (Flowers and Yeo, 1986).

Salinity stress interfere the uptake and accumulation of essential nutrients (Shannon and Grieve, 1999). Generally, $Ca^{2+}$ and $K^+$ are decreased in plants under saline conditions. These decreases could be due to the antagonism of $Na^+$ and $K^+$ at uptake sites in the roots, the effect of $Na^+$ on $K^+$ transport into the xylem or the inhibition of uptake processes (Al-Harbi, 1995).

Additional Potassium application affected on the percent amount of calcium, potassium, magnesium, phosphorus and sodium concentration in mungbean plants (Table-3 & 4). Figures 1-4 and table 3-4 showed that calcium, potassium and magnesium content in leaves, stems, seeds and roots of mungbean under salinity treatments, significantly increased and sodium content decreased with increasing potassium levels.

The mungbean plants chemical analysis revealed that applied saline irrigation water affected ionic concentrations (Table 3&4). Salinity stress caused an increase in $Na^+$ content and a considerable decrease in K+ content, resulting in a significant increase in the $Na^+/K^+$ ratio. The $Na^+$ content was increased in mungbean plants and roots with increasing salinity level with 0% K level. The highest $Na^+$ content was 2.4% for leaves, 9.49% for stems, 2.45% for seeds and 2.89% for roots. In contrast, the $K^+$ content decreased 1.98% for leaves, 2.14% for stems, 1.58% for seeds and 0.28% for roots with increasing salinity level with 0% K level. According to Blumwald et al. (2000), the decrease in $K^+$ concentration due to NaCl may be attributed to a high external $Na^+$ concentration. Wakeel et al.(2011) suggested that the Na+ toxicity affects plant growth, increased $Na^+/K^+$ ratio and thus displacement of $K^+$ by $Na^+$ in the plant cell affects the activity of plasma membrane (PM) $H^+$-ATPase.

Addition of 150% and 125% $K^+$ to the highest salinity stressed plants reduced the $Na^+$ (1.26% for leaves, 1.66% for stems, 1.94% for seeds and 1.78% for roots and 1.75% for leaves, 1.93% for stems, 2.13% for seeds and 1.88% for roots respectively) and increased K+ (2.56% for leaves, 3.6% for stems, 2.19% for seeds and 0.51% for roots and 2.53% for leaves, 3.45% for stems, 2.18% for seeds and 0.5% for roots respectively) content within plants and roots. Na+/K+ ratio increased (1.21% for leaves, 4.43% for stems, 1.55% for seeds and 10.32% for roots) with increasing salt doses (12 dS/m) with 0% K level. Therefore, it can be said that, the elevation of KCl concentration in the saline nutrient solution has been proven to be effective in increasing $K^+/Na^+$ ratio in mungbean plants and roots. However, this increased ratio influenced mungbean yield and all other growth parameters.

Table 3. Chemical composition of mungbean leaves and stem as affected by the application of K under saline irrigation water

| | Leaf nutrient content (%) | | | | | | Root nutrient content (%) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Treatments** | **Ca** | **Mg** | **K** | **P** | **Na** | **Na:K** | **Ca** | **Mg** | **K** | **P** | **Na** | **Na:K** |
| $T_1$ | 6.89 | 3.38 | 3.71 | 1.2 | 0.33 | 0.09 | 7.44 | 3.38 | 8.75 | 1.33 | 0.45 | 0.05 |
| $T_2$ | 3.44 | 2.31 | 2.9 | 0.88 | 1.18 | 0.41 | 3.05 | 1.68 | 2.73 | 0.77 | 3.13 | 1.15 |
| $T_3$ | 3.68 | 2.54 | 3.17 | 0.93 | 1.03 | 0.32 | 3.94 | 2.14 | 4.55 | 0.91 | 2.92 | 0.64 |
| $T_4$ | 4.77 | 2.87 | 3.23 | 1 | 0.99 | 0.31 | 4.13 | 2.57 | 4.61 | 1 | 2.39 | 0.52 |
| $T_5$ | 5.02 | 3.02 | 3.41 | 1.18 | 0.87 | 0.26 | 5.66 | 3.38 | 5.05 | 1.05 | 2.05 | 0.41 |
| $T_6$ | 2.08 | 1.98 | 2.37 | 0.61 | 1.58 | 0.67 | 2.44 | 1.58 | 2.62 | 0.64 | 5.36 | 2.05 |
| $T_7$ | 3.26 | 2.06 | 2.67 | 0.67 | 1.31 | 0.49 | 3.67 | 1.67 | 4.07 | 0.68 | 4.03 | 0.99 |
| $T_8$ | 4.08 | 2.19 | 2.81 | 0.77 | 1.2 | 0.43 | 4.13 | 1.79 | 4.07 | 0.69 | 3.82 | 0.94 |
| $T_9$ | 4.38 | 2.37 | 2.96 | 0.82 | 1.34 | 0.45 | 4.7 | 1.88 | 4.27 | 0.86 | 3.56 | 0.83 |
| $T_{10}$ | 1.19 | 1.85 | 1.98 | 0.28 | 2.4 | 1.21 | 1.63 | 0.74 | 2.14 | 0.34 | 9.49 | 4.43 |
| $T_{11}$ | 2.5 | 1.91 | 2.08 | 0.34 | 1.88 | 0.90 | 2.28 | 1.04 | 2.84 | 0.36 | 7.54 | 2.65 |
| $T_{12}$ | 3.03 | 1.97 | 2.53 | 0.43 | 1.75 | 0.69 | 3.13 | 1.39 | 3.45 | 0.59 | 6.66 | 1.93 |
| $T_{13}$ | 3.4 | 2.01 | 2.56 | 0.63 | 1.26 | 0.49 | 3.63 | 1.64 | 3.6 | 0.65 | 5.98 | 1.66 |

Table- 4. Chemical composition of mungbean seeds and roots as affected by the application of K under saline irrigation water

| | Seed nutrient content (%) | | | | | | Stem nutrient content (%) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Treatments** | **Ca** | **Mg** | **K** | **P** | **Na** | **Na:K** | **Ca** | **Mg** | **K** | **P** | **Na** | **Na:K** |
| $T_1$ | 3.41 | 1.55 | 3.13 | 0.87 | 0.28 | 0.09 | 3.29 | 1.49 | 2.03 | 1.03 | 0.61 | 0.30 |
| $T_2$ | 2.21 | 1.01 | 2.01 | 0.62 | 1.27 | 0.63 | 1.8 | 1 | 1.13 | 0.46 | 2.14 | 1.89 |
| $T_3$ | 2.23 | 1.23 | 2.78 | 0.8 | 1.09 | 0.39 | 1.94 | 1.12 | 1.14 | 0.71 | 1.97 | 1.73 |
| $T_4$ | 2.71 | 1.23 | 2.79 | 0.83 | 1.09 | 0.39 | 2.71 | 1.13 | 1.17 | 0.76 | 1.46 | 1.25 |
| $T_5$ | 3.34 | 1.32 | 2.89 | 0.85 | 0.98 | 0.34 | 2.18 | 1.23 | 1.34 | 0.85 | 1.38 | 1.03 |
| $T_6$ | 1.7 | 0.69 | 1.71 | 0.5 | 1.97 | 1.15 | 2.21 | 0.88 | 0.47 | 0.28 | 2.4 | 5.11 |
| $T_7$ | 2.01 | 1.2 | 2.19 | 0.75 | 1.66 | 0.76 | 2.38 | 0.97 | 0.61 | 0.41 | 2.31 | 3.79 |
| $T_8$ | 2.64 | 1.22 | 2.51 | 0.76 | 1.39 | 0.55 | 3.29 | 0.99 | 0.84 | 0.41 | 1.88 | 2.24 |
| $T_9$ | 2.69 | 1.23 | 2.56 | 0.77 | 1.2 | 0.47 | 4.47 | 1.04 | 1.05 | 0.62 | 1.62 | 1.54 |
| $T_{10}$ | 1.25 | 0.57 | 1.58 | 0.47 | 2.45 | 1.55 | 0.67 | 0.31 | 0.28 | 0.15 | 2.89 | 10.32 |
| $T_{11}$ | 1.51 | 0.69 | 2.06 | 0.68 | 2.27 | 1.10 | 1.3 | 0.59 | 0.39 | 0.29 | 1.31 | 3.36 |
| $T_{12}$ | 1.51 | 0.77 | 2.18 | 0.68 | 2.13 | 0.98 | 2.14 | 0.82 | 0.5 | 0.31 | 0.94 | 1.88 |
| $T_{13}$ | 1.97 | 0.89 | 2.19 | 0.71 | 1.94 | 0.89 | 2.5 | 0.94 | 0.51 | 0.36 | 0.91 | 1.78 |

Results showed (table 5) that the saline irrigation increased the EC value of soil. The highest EC value 9.67 at 5 cm depth and 6.52 at 15 cm depth) was obtained from the highest salinity with 0% K level. The application of K affected Na, K, Ca, Mg, P, S, B, Z and ratios of Na:K and Ca:K. The addition of K fertilizers under saline influenced the salts and nutrients dynamics in the soils. A significant decrease in the values of EC, Na, Ca, K, SAR, and increase in pH was observed (Table 5) as compared to control values. The overall higher values of pH in the post-harvest soil might attribute the release of HCO3 and CO3 in the soil. The K in soil solution increased with the addition of K fertilizers (Tables 3). Addition of 150% K increased K in soil from 0.23 to 0.46 at 4 dS/m salinity level, 0.24 to 0.42 at 8 dS/m salinity level and 0.22 to 0.44 at 12 dS/m salinity level. Increases in the soluble K in soil promoted K uptake which could interfere the uptake of other cations (Na, Ca and Mg). These phenomena can reduce adverse effects of the salinity (Abd El-Hadi et al., 2001).

Table- 5. Chemical characteristics of the experimental soil after harvesting of the mungbean

| Treatments | EC dSm | | pH | Ca | Mg | K | P | S | B | Zn | Na | Na:K | Ca:K |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 5 cm | 15 cm | | meq/100ml | | | µg/ml | | | | | | |
| $T_1$ | 0.54 | 0.16 | 6.4 | 4.28 | 2.58 | 0.18 | 257 | 197.3 | 1.3 | 11.6 | 0.44 | 2.44 | 23.78 |
| $T_2$ | 5.04 | 3.98 | 6.4 | 2.63 | 1.65 | 0.23 | 193 | 79.9 | 1.1 | 10.1 | 1.01 | 4.39 | 11.43 |
| $T_3$ | 5.61 | 4.14 | 6.5 | 3.2 | 2.08 | 0.28 | 257 | 111.7 | 1.1 | 11.1 | 0.88 | 3.14 | 11.43 |
| $T_4$ | 5.29 | 2.59 | 6.3 | 3.64 | 2.22 | 0.37 | 241 | 187.2 | 1.2 | 11.3 | 0.81 | 2.19 | 9.84 |
| $T_5$ | 5.06 | 2.59 | 6.5 | 3.87 | 2.43 | 0.46 | 257 | 187 | 1.2 | 11.5 | 0.67 | 1.46 | 8.41 |
| $T_6$ | 5.86 | 3.85 | 6.2 | 2.48 | 1.85 | 0.24 | 205 | 111.5 | 0.98 | 10.3 | 1.49 | 6.21 | 10.33 |
| $T_7$ | 5.74 | 4.77 | 6.3 | 2.78 | 2.11 | 0.37 | 239 | 153 | 0.99 | 11.1 | 1.11 | 3.00 | 7.51 |
| $T_8$ | 6.13 | 3.43 | 6.4 | 3.41 | 2.27 | 0.4 | 249 | 159.9 | 1.1 | 11 | 0.94 | 2.35 | 8.53 |
| $T_9$ | 6.44 | 4.7 | 6.4 | 3.45 | 2.3 | 0.42 | 238 | 182 | **1.1** | 11.3 | 0.89 | 2.12 | 8.21 |
| $T_{10}$ | 8.44 | 3.52 | 6.2 | 2.28 | 0.95 | 0.22 | 188 | 69.3 | 0.92 | 9.8 | 2.27 | 10.32 | 10.36 |
| $T_{11}$ | 8.12 | 6.52 | 6.3 | 3.11 | 1.1 | 0.25 | 199 | 141.9 | 9.7 | 10.3 | 2.05 | 8.20 | 12.44 |
| $T_{12}$ | 9.71 | 5.29 | 6.4 | 3 | 2.07 | 0.34 | 206 | 132.6 | 0.99 | 10.6 | 1.88 | 5.53 | 8.82 |
| $T_{13}$ | 8.16 | 3.44 | 6.5 | 3.33 | 2.08 | 0.44 | 249 | 141.9 | 1.2 | 10.8 | 1.71 | 3.89 | 7.57 |

The saline irrigation water had effect on the Na in soil which increased with saline irrigation and decreased with K treatment (Tables 3). The effect of the addition of KCl was decreased Na in soil solution. Correspondingly, the ratios of Na:K, and Ca:K of soil solution also decreased significantly ($P<0.001$) with K treatments.

## Conclusion

Potassium fertilization can eliminate the deleterious effects of salinity on mung bean yield to some extent. Increasing potassium levels caused an increase in plant fresh weight and dry weight and chlorophyll content, except plant height, root length, number of leaves. Additional K application with saline irrigation water had a positive role on nutrient (Ca, Mg, P and K) uptake, except Na uptake which decreased in response to increasing potassium levels. However, this is only a single year data; therefore, no discreet conclusion can be drawn unless the research runs for few more years.

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# COASTAL GROUNDWATER MANAGEMENT USING AN UNCERTAINTY-BASED COUPLED SIMULATION-OPTIMIZATION APPROACH

D.K. ROY[1], S.K. BISWAS[2] AND B. DATTA[3]

## Abstract

Pumping induced saltwater intrusion in coastal aquifers is a challenging problem, due to the increased abstraction of groundwater resources to meet the growing demand for freshwater supplies. Sustainable beneficial water abstraction from coastal aquifers can be ensured by optimizing water abstraction from a set of production and barrier wells. An optimal pumping management strategy can be prescribed for a coastal aquifer system by utilizing an integrated simulation-optimization (S-O) approach. In this study, the integrated S-O approach was used to develop a saltwater intrusion management model for a real world coastal aquifer system in Barguna district of southern Bangladesh. The aquifer processes were simulated by using a calibrated and validated 3-D finite element based combined flow and solute transport numerical model using the code FEMWATER. The modelling and development of strategies for the management of seawater intrusion processes was performed based on the very limited quantity of available hydrogeological data. The model was calibrated with respect to hydraulic heads for a period of five years from April 2010 to April 2014. The calibrated model was validated for the next three years' period from April 2015 to April 2017. The calibrated and partially validated model was then used within the integrated S-O management model to develop optimal groundwater abstraction patterns to control saltwater intrusion in the study area. Computational efficiency of the management model was achieved by using a MARS based meta-model emulating the combined flow and solute transport processes of the study area. This limited evaluation demonstrates that a planned transient groundwater abstraction strategy, acquired as solution results of a meta-model based integrated S-O approach is useful for developing management strategy for optimized water abstraction, with saltwater intrusion control. This study shows the capability of the MARS meta-model, based an integrated S-O approach, to solve real-life complex coastal aquifer management problems in an efficient manner.

## Introduction

Coastal groundwater is an essential portion of freshwater reserves to meet the need for domestic, agricultural, and industrial supplies to the inhabitants living near the coastal areas. More than 50% of the world's population resides near the coastal areas and this figure will probably rise to 75% during this century (Neumann et al., 2015). This increasing trend in human settlements in the coastal plains inevitably requires more freshwater supplies resulting in overexploitation of the valuable groundwater resources. Overexploitation of coastal groundwater resources may result in saltwater intrusion that may trigger severe repercussions on ecological balance, environmental degradation, and economy of the salinity contaminated areas. A judicial, optimal, and sustainable groundwater withdrawal strategy need to be adopted in coastal aquifers to prevent intrusion of saltwater. A multiple objective management model is capable of prescribing an optimal groundwater withdrawal strategy while confining saltwater concentrations in the aquifer within the acceptable limits. This study proposes a multiple objective saltwater intrusion management model for a coastal aquifer system in Bangladesh.

Bangladesh is primarily an agricultural country, where irrigation plays a vital role in increasing crop productivity. About 90% of this irrigation requirement is fulfilled through groundwater resources (Zahid et al., 2008). The dependency of groundwater in the coastal regions of Bangladesh has been increasing in recent years because surface water use is constrained by contamination with salinity (Rahman et al., 2000) and bacterial contaminants (i.e., pathogens) (Hossain, 2006). Therefore, almost all rural water supplies and a significant part of the urban water supplies are dependent on abstraction of groundwater resources (Roy et al., 2017a). The over-utilization of this groundwater resources inevitably increases the chances of salinity intrusion as the coastal aquifer is hydraulically connected to the sea. The most promising way of preventing salinity intrusion in coastal aquifers is to optimize

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the abstraction of water for beneficial purposes. The optimized water use can be ensured better with the aid of a hydraulic barrier along the coast to prevent saltwater intrusion. Therefore, this study intends to modelling, prediction and management of saltwater intrusion processes in a coastal belt of the Southern part of Bangladesh under very limited hydrogeological data availability. A planned spatial and temporal groundwater abstraction strategy with the utilization of negative hydraulic barriers for controlling saltwater intrusion process is also demonstrated.

Previous studies on saltwater intrusion in coastal aquifers utilized several different approaches either to identify or to control saltwater intrusion. For instance, Al-Juaidi et al. (2014) proposed a regional-scale optimization model to identify water allocations in Gaza Strip. Eissa et al. (2018) proposed an integrative management of saltwater intrusion in poorly-constrained semi-arid coastal aquifer in Egypt. In another study, hydro-geochemical and isotopic tracers were used to identify saltwater intrusion in the paleo beach aquifer in Bangladesh (Seddique et al., 2019). Integration of hydro-geochemical appraisal and multivariate statistical analysis was employed to delineate the influence of saltwater intrusion, saltpans and freshwater for a wetland in India (Kumar et al., 2020). Franceschini and Signorini (2016) conducted a case history to identify the origin of the high chloride content derived from the sea water in areas far from the coast in the Pisa coastal plain (Italy). Dunlop et al. (2019) performed a simulation study of saltwater intrusion in a very complex terrain where mixing of fresh water and saltwater occurs in the lower part of Cauvery.

However, an appropriate management strategy prescribing the optimal groundwater extraction patterns is worth adopting to protect the already vulnerable groundwater resources in coastal aquifers. The integrated simulation-optimization (S–O) technique, among others, is one of the most popular approaches in which numerical models are linked within an optimization framework to obtain optimal groundwater extraction patterns. To achieve computational efficiency, a surrogate or meta-model (emulator) is generally preferable that replaces the computationally intensive simulation model within an integrated S–O approach (Dhar and Datta, 2009). These approximate emulators have been used extensively in the computationally intensive optimization problems (Goel et al., 2007). The commonly used emulators in saltwater intrusion predictions include Support Vector Regression (Lal and Datta, 2020, 2018a; Lin et al., 2019), Gaussian Process Regression (Lal and Datta, 2020, 2018b; Kopsiaftis et al., 2019), and Genetic Programming (Sreekanth and Datta, 2011; Lal and Datta, 2020, 2018b). A number of recent studies have utilized emulator-based integrated S–O approach to develop saltwater management strategies for real-life coastal aquifer systems (Lal and Datta, 2019a, 2019b; 2019c, 2018c). The present study seeks to develop a saltwater intrusion management model for a real-life coastal aquifer in Bangladesh using meta-model based integrated S–O approach where Multivariate Adaptive Regression Spline (MARS) emulators act as replacements of computationally intensive simulation model. MARS provides a fairly authentic reckoning of saltwater intrusion mechanisms for a conceptual multiple layered coastal aquifer system (Roy and Datta, 2017). To the best of the author's knowledge, this is the first effort to implement MARS meta-model in an integrated S–O approach in order to develop saltwater management model for a real-life coastal aquifer system in Bangladesh.

The efficiency and effectiveness of a coupled S–O method not only be determined by the computational efficiency achieved by meta-models but also on the right choice of optimization algorithms. Non- controlled elitist genetic algorithm proposed by Deb et al. (2000) has been successfully used in developing saltwater intrusion management problems in coastal aquifers (Sreekanth and Datta, 2011). The successful use of Controlled Elitist Multiple Objective Genetic Algorithm (CEMOGA) (Deb and Goel, 2001) is also found in recent literature of coastal aquifer management problems (Roy and Datta, 2018). This study uses CEMOGA, which is a variant of non-controlled elitist genetic algorithm (Deb et al., 2000).

The Pareto optimal front produced by the CEMOGA provides a huge total of Pareto optimal solutions. Therefore, eliminating less significant trade-offs and selecting the most suitable solution(s) require detailed understanding of the nature of the conflicting objectives. However, the decision-making process can be made easier for the decision makers through providing a post-Pareto analysis of the developed management model. Very few of the multiple objective saltwater intrusion management models focused on the choice of optimal solution(s) from the Pareto front, e.g. by using k-mean clustering approach (Lal and Datta, 2018c). Nonetheless, this approach provides a set of feasible solutions needing further insight of the decision makers in selecting the suitable optimal solution. Decision makers often search for the best solution rather than a set of different feasible solutions. Therefore, in this effort, the selection of the best optimal solution from the Pareto front is proposed by applying the Grey Relational Analysis (GRA) based decision theory.

The prime aim of this study is to demonstrate that it is computationally feasible to develop multiple (two) objective Pareto optimal solutions with conflicting objectives of managing portion of a widely used coastal aquifer, where salinity intrusion due to unplanned withdrawal is a threat to sustainable use of groundwater resources.

**Methodology**

The integrated simulation-optimization (S-O) approach (Dhar and Datta, 2009) is the core constituent of the present study. The study applies this integrated S-O approach in order to develop optimal pumping management schemes for a real world coastal aquifer system. The basic components of the adopted S-O approach are: (1) a finite element based 3-D numerical simulation model to simulate the physical processes, (2) a properly trained and validated meta-model that approximates numerically simulated salinity concentrations at designated monitoring locations, and (3) an optimization algorithm to search for the optimal groundwater extraction patterns from the aquifer. Brief descriptions of each of these components are provided in the subsequent paragraphs.

***Numerical simulation model***

Aquifer processes are simulated using a density dependent finite element-based 3D coupled flow and salt transport numerical simulation model, FEMWATER (Lin et al. 1997). The simulation model generates salinity concentrations at designated monitoring locations using randomized groundwater extraction values as inputs obtained from the Latin Hypercube Sampling (LHS) technique (Pebesma and Heuvelink 1999). The governing equations of the combined flow and salt transport processes are expressed as (Lin et al. 1997):

$$\frac{\rho}{\rho_0} F \frac{\partial h}{\partial t} = \nabla . \left[ K . \left( \nabla h + \frac{\rho}{\rho_0} \nabla z \right) \right] + \frac{\rho}{\rho^*} q \qquad (1)$$

$$F = \alpha' \frac{\theta}{n} + \beta' \theta + n \frac{dS}{dh} \qquad (1)$$

where, $F$ = storage coefficient, $h$ = pressure head, $K$ = hydraulic conductivity tensor, $z$ = potential head, $q$ = a source or a sink, $\rho$ = water density at chemical concentration $C$, $\rho_0$ = referenced water density at zero chemical concentration, $\rho^*$= density of injection fluid or that of the withdrawn water, $\theta$ = moisture content, $\alpha'$ = modified compressibility of water, $\beta'$ = modified compressibility of the medium, $n$ = porosity, $S$ = saturation.

The hydraulic conductivity tensor, $K$ is represented by

$$K = \frac{\rho g}{\mu} k = \frac{(\rho/\rho_0)}{\mu/\mu_0} \frac{\rho_0 g}{\mu_0} k_s k_r = \frac{\rho/\rho_0}{\mu/\mu_0} k_{so} k_r \qquad (2)$$

where, $\mu$ = dynamic viscosity of water at chemical concentration $C$, $\mu_0$ = reference dynamic viscosity at zero chemical concentration, $k_s$ = saturated permeability tensor, $k_r$ = relative permeability or relative hydraulic conductivity, $k_{so}$ = referenced saturated conductivity tensor.

Both the dynamic viscosity and density of water vary with the chemical concentration. They take the form of the following two equations

$$\frac{\rho}{\rho_0} = a_1 + a_2C + a_3C^2 + a_4C^3 \quad (3)$$

$$\frac{\mu}{\mu_0} = a_5 + a_6C + a_7C^2 + a_8C^3 \quad (4)$$

where, $a_1, a_{2,\dots,}a_8$ indicates the coefficients that defines the dependence of density and viscosity of water on chemical concentration; and $C$ represents the chemical concentration.

The Darcy velocity term $V$ is given by the following equation

$$V = -K.\left(\frac{\rho_0}{\rho}\nabla h + \nabla z\right) \quad (5)$$

The 3-D solute transport equation is expressed as

$$\theta\frac{\partial C}{\partial t} + \rho_b\frac{\partial S}{\partial t} + V.\nabla\text{C} - \nabla.(\theta D.\nabla\text{C})$$

$$= -\left(\alpha'\frac{\partial h}{\partial t} + \lambda\right)(\theta C + \rho_b S) - (\theta K_w C + \rho_b K_s S) \quad (6)$$

$$+m - \frac{\rho^*}{\rho}qC + \left(F\frac{\partial h}{\partial t} + \frac{\rho_0}{\rho}V.\nabla\left(\frac{\rho}{\rho_0}\right) - \frac{\partial C}{\partial t}\right)C$$

where, $\rho_b$ = bulk density of the medium, $C$ = material concentration in aqueous phase, $S$ = material concentration in adsorbed phase, $t$ = time, $V$ = discharge, $\nabla$ = del operator, $D$ = Dispersion coefficient tensor, $\lambda$ = decay constant, $M = qC_m$ = artificial mass rate, $q$ = source rate of water, $C_m$ = material concentration in the source, $K_w$ = first order biodegradation rate constant through dissolved phase, $K_s$ = first order biodegradation rate through adsorbed phase, $K_d$ = distribution coefficient.

The dispersion coefficient tensor $D$ in equation (6) is expressed as

$$\theta D = a_T|V|\delta + (a_L - a_T)\frac{VV}{|V|} + a_m\theta\tau\delta \quad (7)$$

where, $|V|$ = magnitude of $V$, $\delta$ = Kronecker delta tensor, $a_T$ = lateral dispersivity, $a_L$ = longitudinal dispersivity, $a_m$ = molecular diffusion coefficient, and $\tau$ = tortuosity.

***Multivariate Adaptive Regression Spline (MARS)-based meta-model***

MARS is a non-parametric, rapid, and flexible adaptive regression technique (Friedman 1991), which is capable of building regression models by dividing the entire solution space into various intervals of input variables, and builds a regression model by fitting individual Splines or Basis functions to each interval (Bera et al. 2006). MARS based meta-models are able to predict future responses through predictor-response mapping by integrating both a forward and a backward stepwise procedure. To avoid the development of unnecessarily complex model, and to prevent model over-fitting, MARS incorporates the backward stepwise procedure that eliminates irrelevant input variables in determining the output variable (Salford-Systems 2013). Maximum numbers of Basis functions are set as 200 to allow MARS to build a relatively complex model during the forward pass (100 forward steps). Minimum number of observations between the knots is selected by conducting numerical experiments by changing this parameter to a reasonable number of times. No penalty is added to the variables, enabling MARS to give equal priority to all input variables in the forward-stepping process of model development. However, in the backward stepping process MARS sparingly selects the most relevant input variables required to predict the output variables. This backward step keeps the developed model as simple as possible, with less possibility of model over-fitting. A commercial software package, Salford Predictive Modeller® (Salford-Systems 2016) is used to build the MARS models.

For the considered meta-model, training dataset consists 80% of the total input-output patterns generated by utilizing the numerical simulation model, FEMWATER. Remaining 20% of the generated patterns are used for validation of the meta-models. Once training and validation steps are completed, the meta-models thus developed are presented with a totally different realization of test dataset to check the prediction capability. This new realization of test dataset is presented to all developed meta-models to maintain consistency and a fair comparison.

***Management model***

The proposed management model utilizes a linked S/O approach in which a properly trained and validated meta-model is used as an approximate simulator of the aquifer processes. Two conflicting objectives of groundwater extraction strategy are considered: (1) maximum withdrawal of groundwater for beneficial purposes, (2) minimum extraction of water from barrier pumping wells to control saltwater intrusion by establishing a hydraulic head barrier near the coastal boundary. The multi-objective management model provides a tradeoff between these two conflicting objectives in terms of a Pareto optimal front, which consists of several feasible alternative groundwater extraction strategies that meet the pre-specified allowable saltwater concentration limits at specified locations.

***Mathematical formulation***

The mathematical formulation for the proposed saltwater intrusion management methodology is expressed by the following equations (Roy and Datta (2017b)):

$$Maximize: f_1(Q_{PW}) = \sum_{r=1}^{R}\sum_{t=1}^{T} {}_{r}^{t}Q_{PW} \tag{9}$$

$$Minimize: f_2(Q_{BW}) = \sum_{k=1}^{K}\sum_{t=1}^{T} {}_{k}^{t}Q_{BW} \tag{10}$$

Subject to

$$C_i = f(Q_{PW}, Q_{BW}) \tag{11}$$

$$C_i \leq C_{max}\ \forall_i \tag{12}$$

$$Q_{PW}(min) \leq {}_{r}^{t}Q_{PW} \leq Q_{PW}(max) \tag{13}$$

$$Q_{BW}(min) \leq {}_{k}^{t}Q_{BW} \leq Q_{BW}(max) \tag{14}$$

where, ${}_{r}^{t}Q_{PW}$ represents water extraction from the $r^{th}$ pumping well throughout $t^{th}$ time phase; ${}_{k}^{t}Q_{BW}$ stands for water extraction from $k^{th}$ barrier extraction well throughout $t^{th}$ time phase; $C_i$ symbolizes saltwater concentrations at $i^{th}$ monitoring locations at the closure of the management period. Equation (11) indicates salinity concentration is a function of both production and barrier extraction wells; Equation (12) specifies the maximum allowable salt concentration at specified monitoring locations; Equations (13) and (14) provide the lower and upper limits on the water extraction rate from the pumping wells and barrier extraction wells, respectively. Subscripts PW and

BW stand for production bores and barrier extraction wells, respectively. R, $K$, and $T$ stand for the entire pumping wells, barrier extraction wells, and time periods, respectively. The first objective of maximization of groundwater extraction from the pumping wells for beneficial use is represented by Equation *(9)*, and the second objective of minimizing the water extraction from barrier pumping wells is given by Equation *(10)*.

***Optimization algorithm: CEMGA***

Multi-objective optimization of the proposed management model is executed by utilizing a population based search algorithm, Controlled Elitist Multi-objective Genetic Algorithm (CEMGA) (Deb and Goel 2001). The key feature of CEMGA lies in its ability to prefer an individual, who despite having a low fitness value, helps increasing diversity of the population. The diversity is preserved by regulating the populations' elite members during the progress of the algorithm, making new population more diverse. More specifically, this regulated elitist tactic allows a particular fraction of the population (dominated populations) to be part of the current preeminent non-dominated solutions. This inclusion of a particular portion of dominated solutions in the non-dominated solutions greatly reduces the effect of elitism. 'Pareto Fraction' and 'Distance Function' are the two parameters that control the extent of elitism. First parameter restricts the number of individuals (elite members) on Pareto front, whereas the second one is intended to preserve diversity on the Pareto front by giving preference to individuals who are reasonably far-off on the front (Deb and Goel 2001).

***Performance evaluation criteria***

RMSE, Coefficient of Correlation (R), Mean Absolute Percentage Relative Error (MAPRE), Willmott's Index of Agreement (IOA) and Kling–Gupta Efficiency (KGE) are used to evaluate the prediction capability MARS based meta-model. On the other hand, the proposed management models' performance is validated by checking the constraint violation, and by confirming whether the constraints are satisfied at their upper limits. Finally, the optimized pumping values are used with the simulation model to obtain the corresponding saltwater concentration values. These concentration values are compared with those obtained by the meta-model within the optimization framework.

Root Mean Square Error (RMSE) is calculated using

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(C_{i,o} - C_{i,p}\right)^2} \tag{15}$$

Correlation Coefficient (R) is expressed as

$$R = \frac{\sum_{i=1}^{n}\left(C_{i,o} - \overline{C_o}\right)\left(C_{i,o} - \overline{C_p}\right)}{\sqrt{\sum_{i=1}^{n}\left(C_{i,o} - \overline{C_o}\right)^2}\sqrt{\sum_{i=1}^{n}\left(C_{i,p} - \overline{C_p}\right)^2}} \tag{16}$$

Mean Absolute Percentage Relative Error (MAPRE) is calculated as

$$MAPRE = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{C_{i,o} - C_{i,p}}{C_{i,o}}\right| \times 100 \tag{17}$$

Willmott's Index of Agreement (IOA) is calculated as

$$IOA = 1 - \frac{\sum_{i=1}^{n}\left(C_{i,o} - C_{i,p}\right)^2}{\sum_{i=1}^{n}\left(\left|C_{i,p} - \overline{C_o}\right| + \left|C_{i,o} - \overline{C_o}\right|\right)^2} \tag{18}$$

The Kling-Gupta Efficiency coefficient (KGE) is calculated as

$$KGE = 1 - ED = 1 - \sqrt{(R-1)^2 + (\propto -1)^2 + (\beta - 1)^2} \tag{19}$$

$$\propto = \frac{\sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(C_{i,P} - \overline{C_P}\right)^2}}{\sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(C_{i,O} - \overline{C_O}\right)^2}} \tag{20}$$

$$\beta = \frac{\frac{1}{n}\sum_{i=1}^{n} C_{i,P}}{\frac{1}{n}\sum_{i=1}^{n} C_{i,O}} \tag{21}$$

where, $C_{i,O}$ and $C_{i,P}$ are the observed and predicted saltwater concentrations (mg/l); $\overline{C_O}$ and $\overline{C_p}$ denotes the mean of the observed and predicted saltwater concentrations (mg/l); and *n* represents the number of data points; $ED$ = Euclidian distance from the ideal data points, $\propto$ = relative variability in the simulated and predicted salinity concentration values, $\beta$ = ratio between the mean predicted and mean simulated salinity concentration values representing the bias.

***Parallel computing***

In order to achieve further computational efficiency of the meta-model based linked S/O approach, entire optimization problem is distributed among multiple workers (computational engines for parallel computing) in a parallel pool. In parallel computing, parameters are spontaneously distributed to worker machines throughout the implementation phases of parallel computations. Two conflicting objective functions and all binding constraints of the proposed optimization formulation are solved by utilizing a parallel pool of workers (physical cores of a CPU) by utilizing parallel computing toolbox of MATLAB (MATLAB 2021a-b).

***Study area***

The study area is located in Barguna district, one of the coastal districts of Bangladesh. It is located in the southern part of Bangladesh, lying between 21º48′ and 22º29′ north latitudes and between 89º52′ and 90º22′ east longitudes, and is also within the tropics. The land area is nearly flat, having rivers and estuarine creeks with regular low and high tides. The Barguna district belongs to the Gangetics tidal floodplain that is highly susceptible to storms and tidal flooding. The coastal aquifer is contaminated by salinity intrusion resulting from large amounts of extraction. The study area consists of two upazillas (administrative units) in the Barguna district: Patharghata (258.63 $km^2$) and Barguna sadar (339.54 $km^2$). The southern part of the study area is surrounded by the mangrove forest and the Bay of Bengal. The aerial map of the study area is presented in Figure 1.

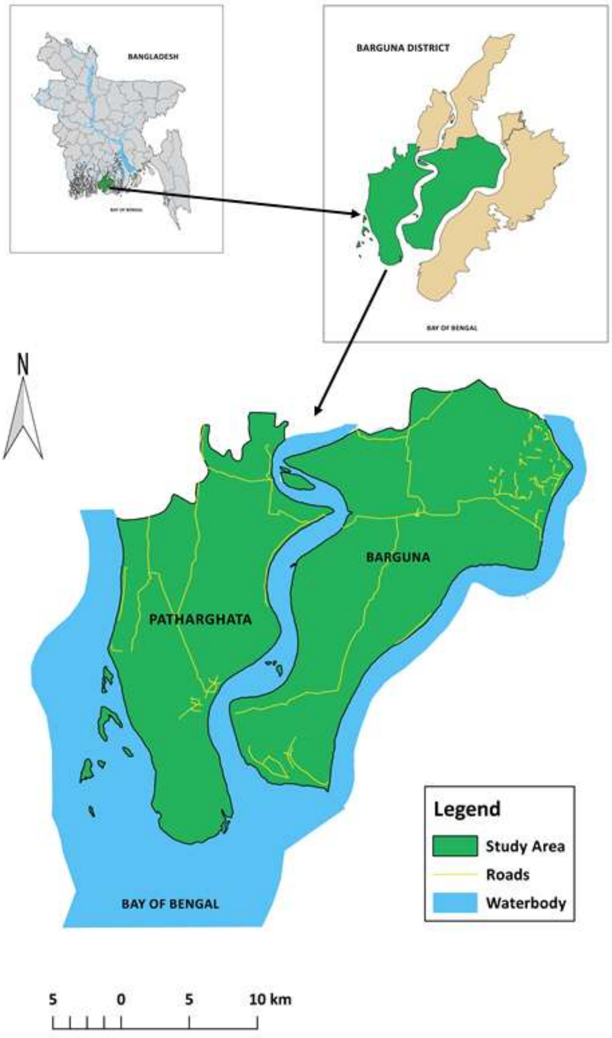


Figure 1. Location and aerial map of the study area

During the wet monsoon season, water enters the study area through recharge from rainfall and the water discharges into the river systems (Faneca Sanchez et al., 2015). In contrast, the study area receives water through infiltration from the rivers during the dry cold seasons, the quality of groundwater depending on the salt concentration of the surface water. Groundwater abstraction has very little influence (only 4%) on the water balance of the study area in the wet monsoon season. In the dry season, groundwater abstraction accounts for about 50-70% of groundwater leaving the study area (Faneca Sanchez et al., 2015). Many wells are in use in each village, each shared by a single family or a group of several families, and 97% of the rural population uses groundwater for its water supply (Kinniburgh et al., 2003). Deep tube well depths range between 60-100 m whereas shallow tube well depths range between 10-60 m (Kinniburgh and Smedley, 2001; Mondal and Saleh, 2003).

## Modelling of saltwater intrusion processes

### *Model development*

The major difficulty in developing a regional scale saltwater intrusion model is the scarcity of reliable data for hydrogeological parameters and groundwater use in the area. Data from various sources were utilized in the model development, based on the best possible subjective judgement. Hydraulic head data for a period of eight years (April 2010 to April 2017) were collected from the website of the Processing and Flood Forecasting Circle of Bangladesh Water Development Board (BWDB) (Bangladesh Water Development Board. Processing and Flood Forecasting Circle, 2018). Two hydraulic head values were obtained for the study area (one from each upazilla). The observation well at Patharghata upazilla is located at 22° 11' 8" north latitude and 89° 59' 21" east longitude. The other observation well at Barguna sadar upazilla is located at 22° 9' 26" north latitude and 90° 6' 2"east longitude. Surface water level and salinity data were collected from the website of BWDB (Bangladesh Water Development Board. Processing and Flood Forecasting Circle, 2018). Based on the data, a specified head was assigned at the upstream end of the river and interpolated over the lengths of the river. A constant concentration of river water salinity was assumed. There are three distinct seasons in Bangladesh: 1) a cold dry winter from November to February, 2) a humid hot summer from March to May and 3) a cool rainy monsoon season from June to October. These seasonal variations only affect the top layers of the aquifer (Faneca Sanchez et al., 2015). Therefore, the average values of the parameters for these three different seasons were used in this study.

Previous studies in the Bengal Delta modelled a very large area (Faneca Sanchez et al., 2015; Michael and Voss, 2009) by assuming groundwater abstraction per unit area of the model domain. The withdrawals were distributed based on estimates made for each administrative unit. Of note, it is difficult to represent pumping in the model domain as individual wells because of the large number of unreported wells and the large scale of the study area. However, the main aim of this study was to prescribe optimal groundwater abstraction patterns to control saltwater intrusion. In addition, the implementation of hydraulic control measures in the form of barrier abstraction wells was also used as a measure of salinity control. Therefore, the exact location of the point pumping was approximated in the present study based on the land use pattern of the study area. In conformance with the total water abstraction and for simplicity in the model, total water abstraction was distributed among the individual wells during the calibration and validation processes. Groundwater abstractions were calculated from domestic, industrial, and agricultural water use. Total domestic and industrial pumping rates were based on estimates of population and per capita water consumption rates (Michael and Voss, 2009). Total domestic and industrial demand were taken as 50 l/day/capita (Faneca Sanchez et al., 2015; Michael and Voss, 2009) and assumed constant throughout the year. Total population for the study area were obtained by using data from the population census of the district statistics of Bangladesh (Bangladesh Bureau of Statistics (BBS), 2013). A population growth rate 2.09% per year (Michael and Voss, 2009) was used to calculate the number of population in subsequent years of simulation. Total domestic and industrial water abstraction was calculated from the following equation

$$\begin{aligned} Q_{domestic+industrial}&(m^3/day) \\ &= Population\ size \times Annual\ growth\ rate \\ &\times Per\ capita\ water\ demand \end{aligned} \qquad (22)$$

The amount of water abstraction for irrigation purposes was computed from the total irrigated portion of the study area multiplied by the quantity of applied water to the irrigated area during the crop growing season (Michael and Voss, 2009). Total irrigated area in the study area was obtained from the district statistics for Barguna district (Bangladesh Bureau of Statistics (BBS), 2013). The total irrigated area was multiplied by an abstraction rate of 1 m/pumping season/$m^2$ of irrigated area (Harvey et al., 2006).

The type and thickness of aquifer material layers were chosen in accordance with the lithological data of the study area. It is noted that up to 300m depth of the study area falls under alluvium soil type composed mainly of clay, silt, sand, and occasional gravel (Faneca Sanchez et al., 2015). As most of the physical processes are occurred in the first few meters of the aquifer, an aquifer thickness of 150 m was chosen. The total thickness of the aquifer was divided into four layers of materials. First layer below the ground surface belongs to sandy silt with a thickness of 40 m, followed by a layer of sandy loam with 50 m thickness, followed by a soil type of sand with a thickness of 40 m. The bottom layer was specified as sandy clay with a thickness of 20 m. An average value of hydraulic conductivity was assigned to each model layer. The aquifer material within each model layer was assumed homogeneous, only vertical heterogeneity in terms of hydraulic conductivity was considered. The hydraulic conductivity values used in this study were in accordance with previous studies conducted in the Bengal Delta (Faneca Sanchez et al., 2015; Michael and Voss, 2009). An anisotropy ratio ($kx/ky$) = 2.0 was used, where $kx$ represents the horizontal hydraulic conductivity in the $X$-direction. $ky$ is the horizontal hydraulic conductivity in the $Y$-direction. $kz$ is the vertical hydraulic conductivity in the $Z$-direction. The value of $kz$ was taken as one tenth of the hydraulic conductivity values in the $X$-direction. The 3-D view of the model domain with finite element meshes is illustrated in Figure 2.

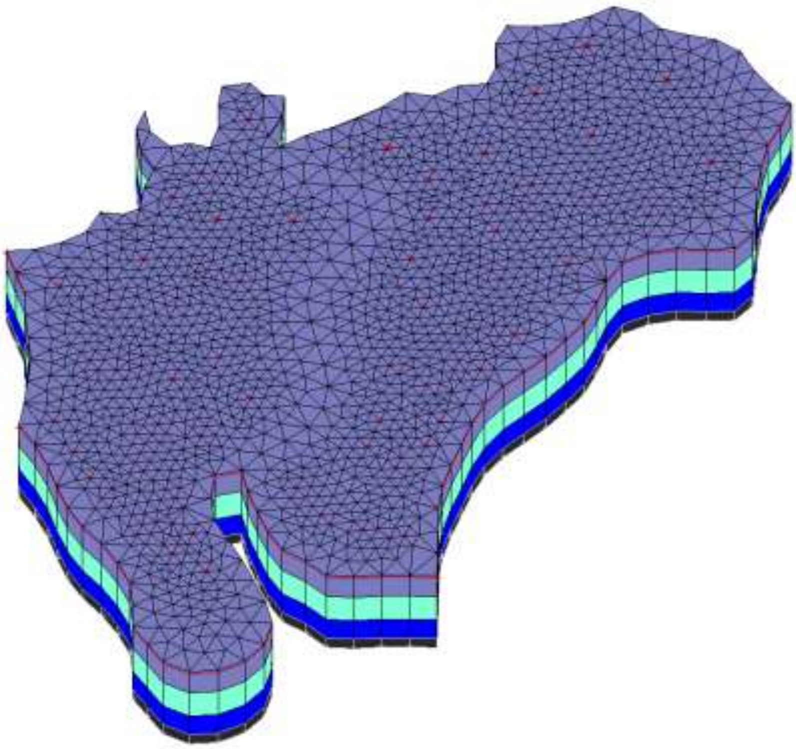

Figure 2. Three dimensional view of the study area

The study area is bounded by the Bay of Bengal in the southern side, Burishwar River in the eastern side, and Haringhata River in the western side. A river named Bishkhali is flowing in the middle part of the study area separating the two administrative upazillas. The Northern boundary is the administrative boundary, which was specified as the no flow boundary. Although it is very difficult to conclude that the northern boundary is a no flow boundary, the no flow boundary condition was assumed based on the consideration that the study area has a negligible hydraulic gradient (around 1:20000) in the vicinity of this boundary. Therefore, lateral movement of groundwater across this boundary, as shown in Figure 1, can be considered as negligible (Faneca Sanchez et al., 2015). Therefore, for modelling purposes, this northern boundary as shown in Figure 1 was assumed as a no flow boundary. In addition, the northern boundary is relatively far away from the sea face boundary. Moreover, the calibration-validation process did not show that it was an unreasonable assumption. The seaside boundary was assigned as a constant head and constant concentration boundary. Constant head and constant concentration values in the seaside boundary were specified as zero (MSL) and 35000 mg/l, respectively. The upstream ends of the rivers were assigned specified head values that varied linearly along the stream and ended at zero meter at the seaside boundary. Specified heads of 0.8 m, 0.86 m, and 0.70 m were assigned at the upstream ends of Haringhata, Bishkhali, and Burishwar Rivers, respectively. The tidal river salinity concentrations were specified as 10000 mg/l and assumed to be constant throughout the simulation period. The fluid properties used in this study are presented in Table 1.

Table 1. Fluid properties

| Parameters | Units | Values |
|---|---|---|
| Density of freshwater | $Kg/m^3$ | 1000 |
| Density of seawater | $Kg/m^3$ | 1028 |
| Dynamic viscosity of water | Kg/m–day | 131.328 |
| Compressibility of water | $m–day^2/kg$ | $6.69796 \times 10^{-20}$ |
| Density reference ratio | dimensionless | 0.025 |

A plan view of the study area with boundaries and wells is shown in Figure 3. In Figure 3, the production wells, barrier wells, and monitoring locations are indicated by P1-P43, B1-B13, and M1-M16, respectively. For calibration and validation purposes, barrier well pumping was not considered and the hydraulic heads were observed at monitoring locations M1 and M2. Once proper calibration and validation were performed, barrier extraction wells were introduced as the hydraulic control measures of the saltwater intrusion processes. Moreover, an additional 14 monitoring locations were used to monitor salinity concentrations for developing the saltwater intrusion management model for the study area.

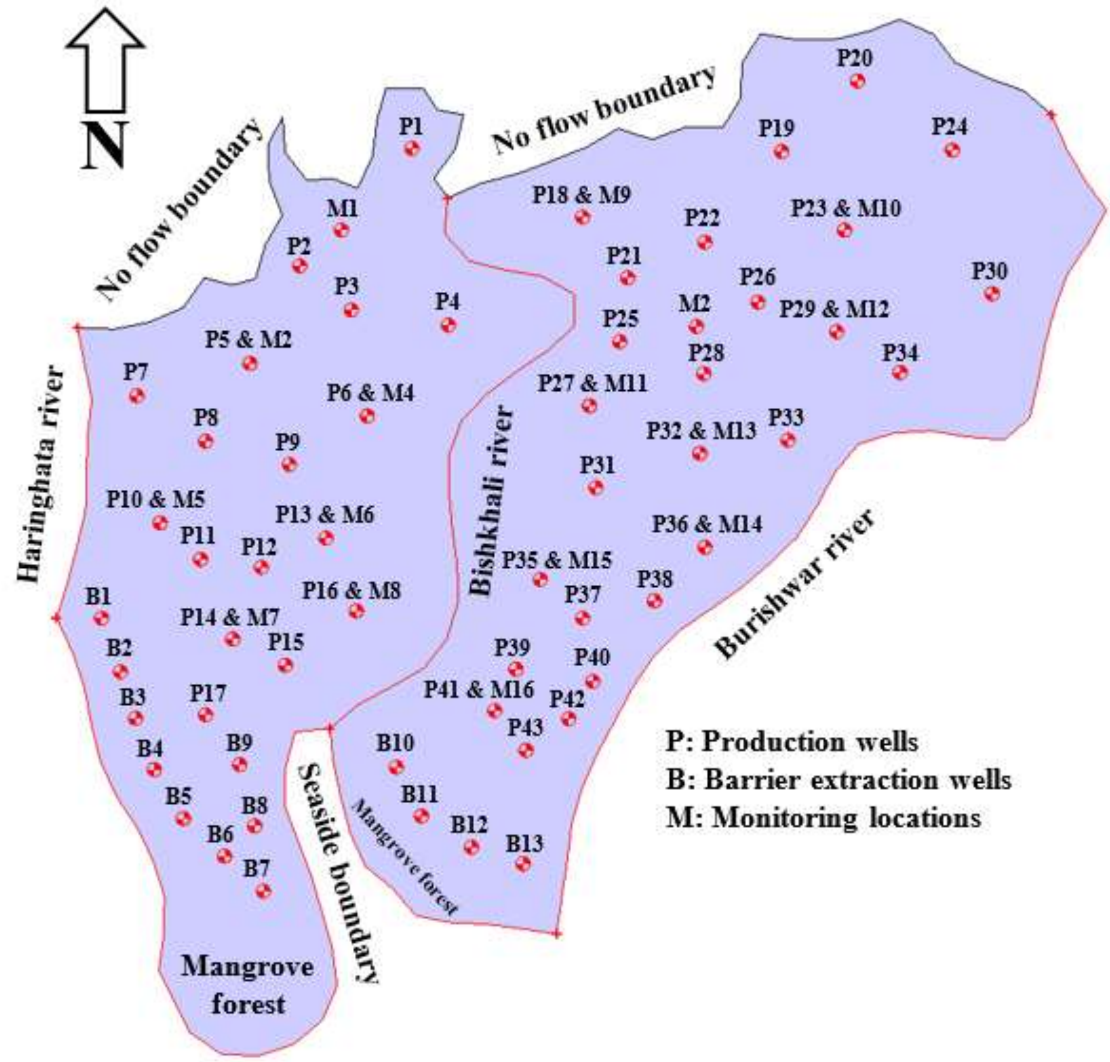


Figure 3. Plan view of the study area showing the boundaries and wells

***Mesh dependency test***

The accuracy of numerical simulation models often depends on the size of the finite elements. However, finer mesh size is associated with additional computational requirements. Therefore, modelling should be performed by maintaining a balance between accuracy and computational requirement. For this, the mesh dependency of the simulated hydraulic heads was determined by conducting numerical experiments, utilizing element sizes of 600m, 800m, 1000m, and 1200m. The simulation was performed for a period of 10 years, with a constant groundwater abstraction rate of 4000 $m^3$/day from each of the 43 production wells. Hydraulic heads and the time required for simulating the aquifer processes at the end of the simulation period were computed at two monitoring locations M1 and M2, and are presented in Table 2. Table 2 shows that the computed hydraulic heads did not vary significantly when different element sizes were used. However, there was a substantial increase in simulation times with the increase in element size. Considering the computation time and accuracy of simulation, an element size of 1200 m was used in the present study.

Table 2. Hydraulic heads and simulation times with different element sizes

| Element size, m | Hydraulic heads, m | | Simulation time, min |
|---|---|---|---|
| | Patharghata (M1) | Barguna Sadar (M2) | |

| | | | |
|---|---|---|---|
| 1200 | 2.823 | 2.598 | 13.05 |
| 1000 | 2.825 | 2.597 | 18.57 |
| 800 | 2.826 | 2.598 | 29.58 |
| 600 | 2.825 | 2.598 | 47.95 |

*Model calibration*

The calibration process was initiated from a steady state condition of the hydraulic heads in the finite element nodes of the model domain. To achieve this condition, the transient simulation model was run for 80 years (April 1930 to April 2009). The simulation was performed in stages with an interval of 10 years. An average value of pumping was used during this simulation period. Outputs at the end of the 10$^{th}$ year's simulation were used as initial conditions for the subsequent intervals of 10 years' period. The process was continued until April 2009, when a stable condition with respect to hydraulic head was achieved. These hydraulic head values at different nodes of the model domain were used as initial conditions for the calibration process. The calibration was performed from a period of five years (from April 2010 to April 2014). The hydraulic heads were monitored at the designated monitoring locations (M1 and M2) on April 2010, April 2011, April 2012, April 2013, and April 2014. Recharge and hydraulic conductivity values were adjusted to obtain the hydraulic heads closer to the actual hydraulic heads in the monitoring locations M1 and M2. Table 3 presents major parameter values used in the calibrated model.

Table 3. Parameter values of the calibrated model

| Parameters | Values | Units |
|---|---|---|
| Hydraulic conductivity in X-direction for soil layer 1 | 4 | m/day |
| Hydraulic conductivity in X-direction for soil layer 2 | 10 | m/day |
| Hydraulic conductivity in X-direction for soil layer 3 | 15 | m/day |
| Hydraulic conductivity in X-direction for soil layer 4 | 8 | m/day |
| Aquifer recharge applied on the top soil layer | 0.000689 | m/day |
| Longitudinal dispersivity | 80 | m |
| Lateral dispersivity | 30 | m |
| Molecular diffusion coefficient | 0.69 | $m^2$/day |

Actual and simulated hydraulic heads at two upazillas (M1 and M2 in Figure 3) during the calibration process are presented in Figure 4.

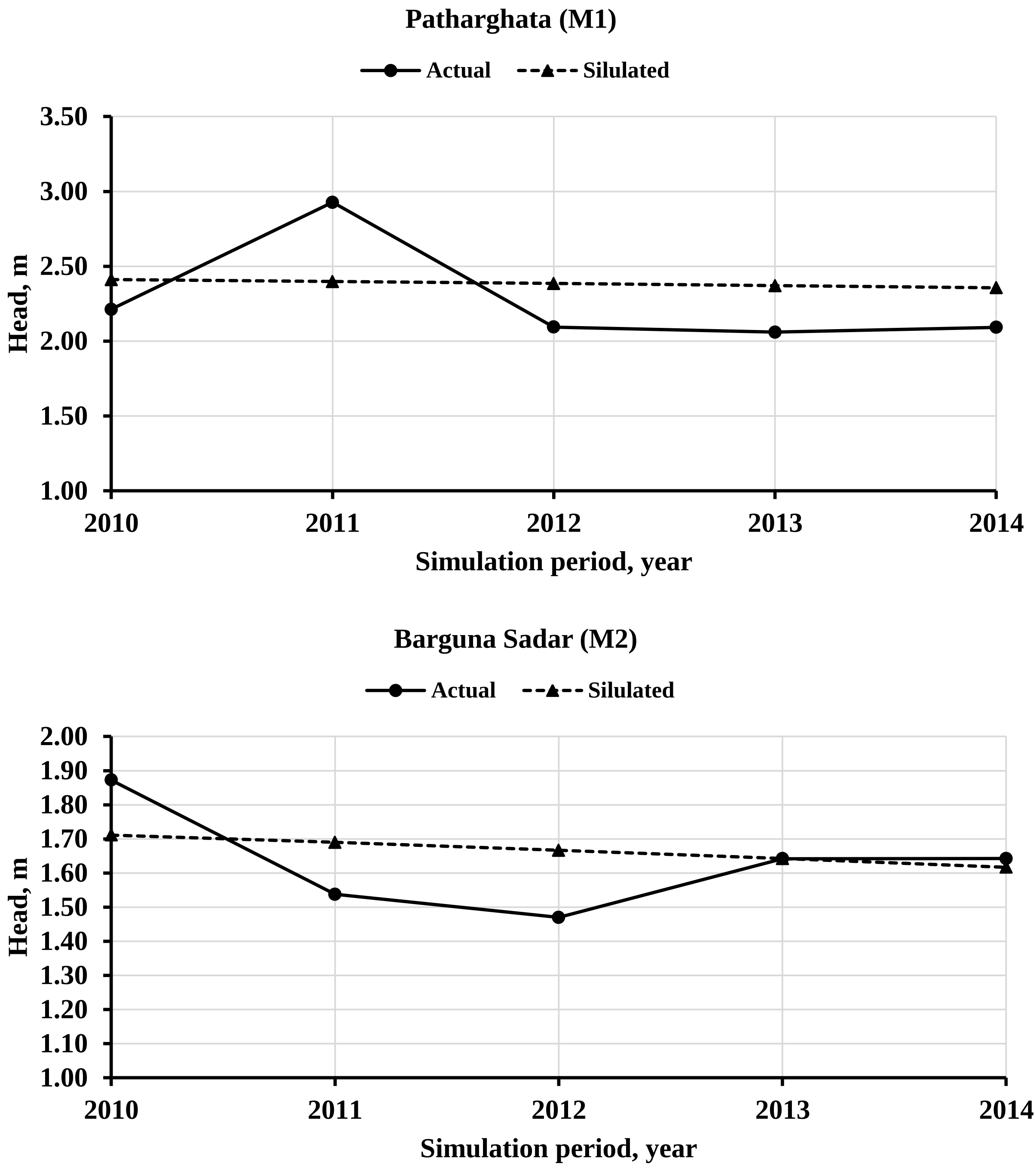


Figure 4. Actual and simulated hydraulic heads at two upazillas during the calibration process.

The calibrated model was then validated for the next three years from April 2015 to April 2017. Outputs in terms of hydraulic heads on April 2014 were used as the initial condition for the simulation of the validation period. The model boundary conditions remained same as the calibrated model. At the end of the simulation period, the hydraulic heads were monitored at monitoring locations M1 and M2 in April 2015, April 2016, and in April 2017. Hydraulic heads during the validation process is presented in Figure 5.

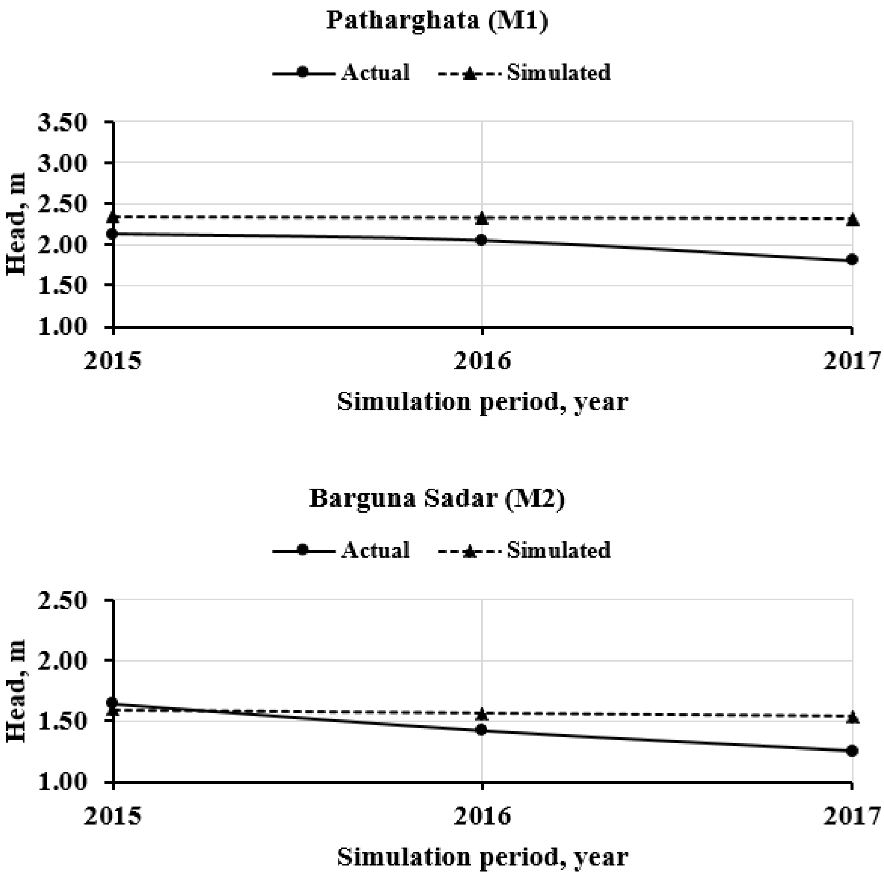


Figure 5. Actual and simulated hydraulic heads at two upazillas during the validation period.

The calibration and validation processes were performed by using a uniform time step of 5 days' interval. A smaller time step is associated with higher computational time requirements and vice versa. Computational time is an issue in situations where multiple simulations of the aquifer processes with different sets of transient pumping values are required to train and test a meta-model for using in an integrated S-O approach. Therefore, a sensitivity analysis was performed to evaluate the effects of time steps of simulation on the computed hydraulic heads. Time steps of 1 day, 5 days, 10 days, and 73 days were used to simulate the hydraulic heads during the calibration periods from April 2010 to April 2014. The results are presented in Table 4.

Table 4. Sensitivity of simulation time steps to simulated hydraulic heads

| Calibration period | Hydraulic heads, m | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Patharghata | | | | Barguna Sadar | | | |
| | 1 day | 5 days | 10 days | 73 days | 1 day | 5 days | 10 days | 73 days |
| 2010 | 2.41155 | 2.41105 | 2.41121 | 2.41094 | 1.71220 | 1.71135 | 1.71163 | 1.71120 |
| 2011 | 2.39968 | 2.39483 | 2.39844 | 2.39858 | 1.69179 | 1.68964 | 1.68968 | 1.68995 |
| 2012 | 2.38669 | 2.38463 | 2.38484 | 2.38503 | 1.66941 | 1.66588 | 1.66625 | 1.66661 |
| 2013 | 2.37317 | 2.37035 | 2.37030 | 2.37094 | 1.64606 | 1.64120 | 1.64112 | 1.64227 |
| 2014 | 2.35933 | 2.35583 | 2.35581 | 2.35645 | 1.62204 | 1.61599 | 1.61597 | 1.61712 |

Table 4 shows that the estimates of hydraulic heads did not differ substantially among different time steps during the calibration periods. However, a considerable amount of computational efficiency was achieved when a simulation time step of 73 days was used. Time taken to simulate the aquifer processes for the time steps of 1 day, 5 days, 10 days, and 73 days were 14.61 min, 4.82 min, 3.17 min, and 0.95 min, respectively. Therefore, simulation time steps of 73 days were used in the multiple simulations with different transient pumping values. These multiple simulations were used to generate input-output training patterns for training of the meta-model.

**Generation of input-output patterns for training of MARS meta-models**

The physical processes of the aquifer with the transient groundwater abstraction patterns were simulated for the specified management period in order to generate input-output training patterns for MARS based meta-models. The spatial and temporal pumping stress applied to the aquifer was associated with water abstraction from a set of production, and barrier wells at specific locations and time steps. The transient groundwater abstraction values were obtained through Halton sequences (HA) (Halton, 1960), with specified lower and upper bounds. The HA are based on a deterministic algorithm, which uses prime numbers as bases for each dimension. This sampling technique was used in the current study because of its superiority over commonly used sampling techniques (Loyola R et al., 2016). The samples obtained by using the HA approach were found to be more uniform compared to Latin Hypercube Sampling (LHS) (Pebesma and Heuvelink, 1999). A comparison of the sampling sequences by utilizing both LHS and HA is provided in Figure 6.

The transient abstraction values were fed into the simulation model as inputs in order to obtain saltwater concentration values as outputs at specified monitoring locations. One set of input-output patterns was obtained from the transient groundwater abstraction values and the corresponding salinity concentrations. The salinity concentrations were measured at 16 monitoring locations. A number of such patterns were obtained by simulating the aquifer processes multiple times with different sets of transient groundwater abstraction values from a combination of production and barrier wells. The aquifer properties as well as the initial and boundary conditions remained constant for different simulations. Only the transient groundwater abstraction values varied in subsequent simulations to acquire different realizations of resulting saltwater concentration values obtained solely due to the pumping stress applied to the aquifer.

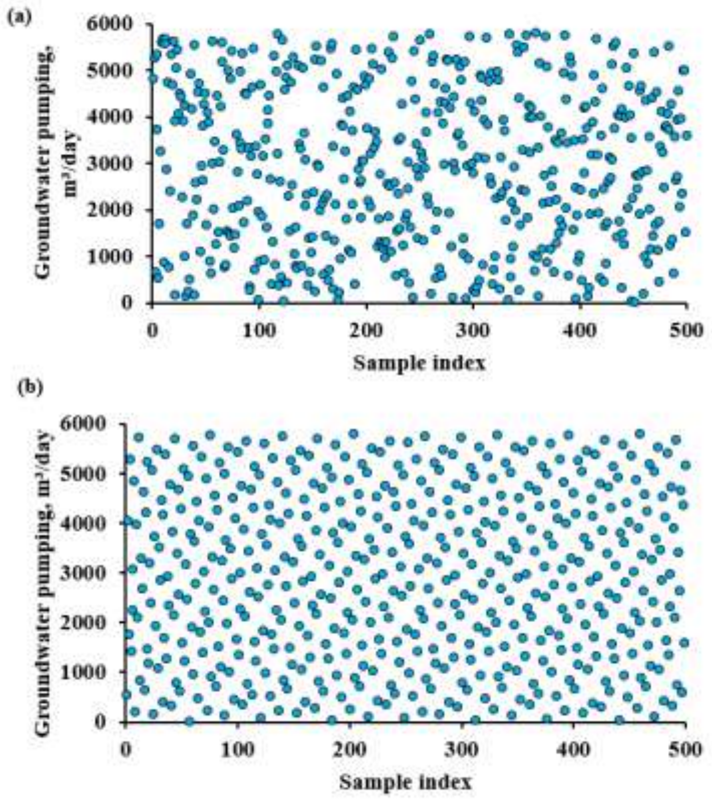


Figure 6. Sampling sequences generated using (a) Latin hypercube sampling, (b) Halton sampling

## Performance of the MARS meta-models

The capability of the MARS meta-models in approximating coupled transient flow and solute transport processes in the coastal aquifer system was evaluated by using different statistical indices. After proper training and validation, the meta-models were presented with an unseen test dataset. For performance evaluation purposes, the R, IOA, KGE, RMSE, and MAPRE values were calculated for the developed meta-models on this new test dataset. The results are presented in Table 5. Generally, MARS meta-models produced higher values of R, IOA, KGE and lower values of MAPRE and RMSE at all 16 monitoring locations. These results demonstrate the ability of MARS meta-models for capturing the input-output patterns of the transient groundwater abstractions and the corresponding saltwater concentrations at specified monitoring locations.

Table 5. Performance of the MARS meta-models on an unseen test dataset

| Monitoring locations | Performance indices | | | | |
|---|---|---|---|---|---|
| | R | IOA | KGE | RMSE, mg/L | MAPRE, % |
| M1 | 0.99 | 0.99 | 0.99 | 0.005 | 0.0002 |
| M2 | 0.99 | 0.99 | 0.99 | 0.001 | 0.00004 |
| M3 | 0.99 | 0.99 | 0.99 | 0.211 | 0.006 |
| M4 | 0.99 | 0.99 | 0.99 | 0.187 | 0.005 |
| M5 | 0.99 | 0.99 | 0.99 | 0.393 | 0.006 |
| M6 | 0.99 | 0.99 | 0.99 | 0.270 | 0.006 |
| M7 | 0.99 | 0.99 | 0.99 | 0.234 | 0.005 |
| M8 | 0.99 | 0.99 | 0.99 | 0.232 | 0.005 |
| M9 | 0.99 | 0.99 | 0.99 | 0.150 | 0.004 |
| M10 | 0.99 | 0.99 | 0.99 | 0.146 | 0.005 |
| M11 | 0.99 | 0.99 | 0.99 | 0.168 | 0.005 |
| M12 | 0.99 | 0.99 | 0.99 | 0.146 | 0.005 |
| M13 | 0.99 | 0.99 | 0.99 | 0.157 | 0.004 |
| M14 | 0.99 | 0.99 | 0.99 | 0.189 | 0.005 |
| M15 | 0.99 | 0.99 | 0.99 | 0.171 | 0.004 |
| M16 | 0.99 | 0.99 | 0.99 | 0.216 | 0.004 |

As RMSE incorporates both variances and biases of the prediction error, the RMSE criterion was used to evaluate how well MARS meta-models fit the unseen test dataset. Overall, MARS meta-models provide relatively lower RMSE values. However, one of the major drawbacks of RMSE is its tendency to give more weights to the outliers. Therefore, to obtain better information on the prediction capability of MARS meta-models by observing the distribution of errors, the MAPRE criteria were used as another performance measure. MARS meta-models at all monitoring locations provide very small values of MAPRE, which is acceptable in terms of meta-model based prediction accuracies. MARS meta-models' prediction accuracy was also verified from the R, IOA, and KGE viewpoint. All meta-models produced higher values of R, IOA, and KGE indicating the acceptable and reliable prediction accuracies of the developed meta-models.

## Management of saltwater intrusion

The calibrated model was used to develop a saltwater intrusion management model for a period of three years from April 2015 to April 2017. The proposed saltwater intrusion management model considered 168 decision variables of spatial and temporal groundwater abstraction patterns. Variables *X1–X129,* and *X130–X168* represent water abstraction from production and barrier wells, respectively. More specifically, for example, variables *X1–X3* denotes water abstraction from production well P1 in the first, second, and third time steps, respectively. Likewise, variables *X4–X6* denote water abstraction from the production well P2 and so on at three specified time steps. Variables *X130–X132,* *X133–X135, X136–X138…X166–X168* denote water abstraction from barrier wells *B1, B2, B3…B13*, at the first, second, and third time steps.

MARS based meta-models replaced the computationally expensive numerical simulation model within the integrated S-O framework for providing Pareto optimal groundwater abstraction strategies. Sixteen MARS meta-models predicting salinity concentrations at 16 designated monitoring locations were externally linked to CEMOGA in order to predict salinity concentrations. The MARS meta-models were also used to check constraint violations in terms of maximum allowable salinity concentrations at the specified monitoring locations. The CEMOGA used a population size of 2000, crossover fraction of 0.92, and Pareto front population fraction of 0.70. The function and constraint tolerances were set as 1e-5 and 1e-4, respectively. Although a detailed sensitivity analysis was not performed, several trials were conducted to select the optimal set of these parameters. The optimization routine evaluated 20528001 functions in 10263 generations to arrive at the global optimal solution. The optimization routine took 51 minutes to converge to optimal solutions. The Pareto optimal front shown in Figure 7 provided a set of different feasible solutions that show a trade-off between the two contradictory objectives of the saltwater intrusion management problem. The Pareto optimal front in Figure 7 demonstrates that groundwater abstraction from production wells can be increased with increasing the water abstraction from the barrier wells.

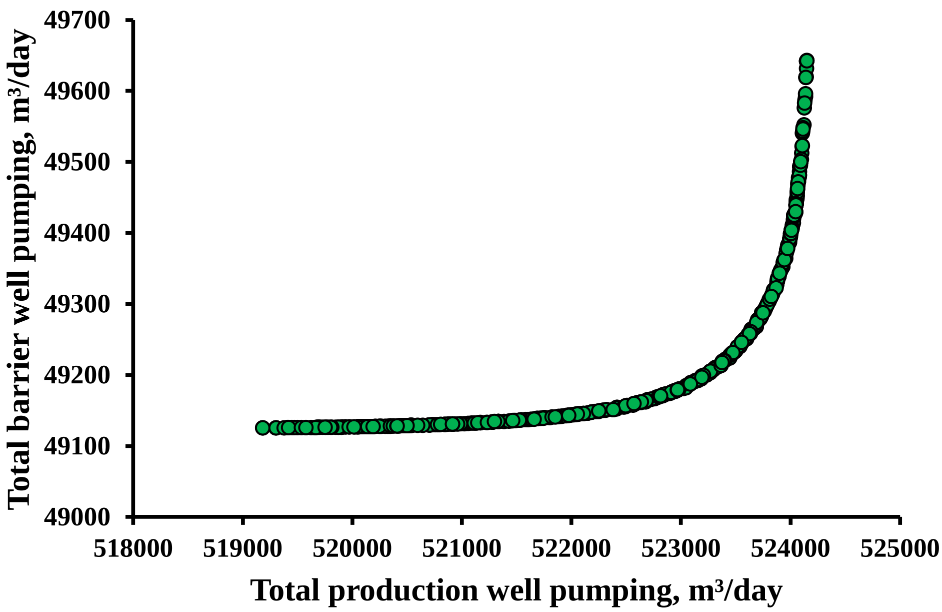


Figure 7. Pareto optimal front of the management model

## Validation of the saltwater intrusion management model

The validity of the proposed saltwater intrusion management model was assessed by observing the actual violation of the constraints. It is noted that the saltwater concentrations obtained from the optimization model solution (determined by MARS meta-models within the optimization framework) were smaller than the pre-specified maximum allowable saltwater concentrations at all monitoring locations. This implies that the imposed constraints were satisfied, and no constraint violation occurred during the search process. Moreover, obtained saltwater concentrations were very close to the prescribed values, which indicate that the optimization model converged to the upper limit of the imposed constraints.

In the second stage, the optimal groundwater abstraction strategies obtained from the optimization model were verified by comparing them with the numerical simulation results. To do this, 10 solutions were selected randomly from different regions of the Pareto optimal front. Table 6 shows the comparison of the MARS predicted and numerical model simulated saltwater concentration values obtained using optimal groundwater abstraction strategies prescribed by the proposed saltwater intrusion management model. Table 6 presents solution results from 5 monitoring locations. The results at other monitoring locations followed a similar trend. It is observed from Table 6 that the solutions obtained from the numerical simulation model were very close to the MARS predictions.

The selection of the best solution from the Pareto optimal front was also proposed by applying decision theory. Gray Relational Analysis (GRA) was used as a decision theory to choose the best optimal solution. GRA is based on Gray system theory proposed by Deng (1982). Gray Relational Coefficient (GRC) as implemented in Wang and Rangaiah (2017) was computed to obtain the best optimal solution. The GRC approach was utilized to find the resemblance between the objective values of each candidate optimal solution and the ideal or best reference objective values.

Table 6. Salinity concentrations calculated from optimal groundwater extraction strategy

| Obs. | Saltwater concentration, mg/l | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | M1 | | M2 | | M3 | | M4 | | M5 | |
| | MARS | SM | MARS | SM | MARS | SM | MARS | SM | MARS | SM |
| 1 | 2584.76 | 2584.77 | 2346.81 | 2346.83 | 3033.77 | 3033.75 | 3234.85 | 3234.77 | 4995.95 | 4996.34 |
| 2 | 2584.76 | 2584.77 | 2346.82 | 2346.83 | 3033.95 | 3033.94 | 3235.04 | 3234.96 | 4995.96 | 4996.34 |
| 3 | 2584.76 | 2584.77 | 2346.82 | 2346.83 | 3033.94 | 3033.93 | 3235.02 | 3234.94 | 4995.96 | 4996.34 |
| 4 | 2584.76 | 2584.77 | 2346.82 | 2346.83 | 3033.94 | 3033.93 | 3235.02 | 3234.94 | 4995.96 | 4996.34 |
| 5 | 2584.76 | 2584.77 | 2346.82 | 2346.83 | 3034.02 | 3034.01 | 3235.05 | 3234.97 | 4995.96 | 4996.35 |
| 6 | 2584.76 | 2584.77 | 2346.81 | 2346.83 | 3033.83 | 3033.81 | 3234.91 | 3234.83 | 4995.95 | 4996.34 |
| 7 | 2584.76 | 2584.77 | 2346.82 | 2346.83 | 3033.95 | 3033.94 | 3235.07 | 3234.99 | 4995.96 | 4996.34 |
| 8 | 2584.76 | 2584.77 | 2346.82 | 2346.83 | 3034.01 | 3034.00 | 3235.06 | 3234.98 | 4995.96 | 4996.34 |
| 9 | 2584.76 | 2584.77 | 2346.81 | 2346.83 | 3033.75 | 3033.74 | 3234.83 | 3234.75 | 4995.94 | 4996.33 |
| 10 | 2584.76 | 2584.77 | 2346.82 | 2346.83 | 3033.94 | 3033.93 | 3235.02 | 3234.94 | 4995.96 | 4996.34 |

*M = Monitoring locations, SM = Simulation model

The GRC calculation is based on the following steps.

Step 1: Standardization of objective values to eliminate the effect of dimensionality. For objective 1 (maximization of total production well abstraction), the standardization was performed as

$$O_{ij} = \frac{O_{ij} - \min_{i\epsilon m} O_{ij}}{\max_{i\epsilon m} O_{ij} - \min_{i\epsilon m} O_{ij}} \tag{23}$$

The standardization of objective 2 (minimization of total barrier well abstraction) is expressed as

$$O_{ij} = \frac{\max_{i\epsilon m} O_{ij} - O_{ij}}{\max_{i\epsilon m} O_{ij} - \min_{i\epsilon m} O_{ij}} \tag{24}$$

Step 2: Searching for the ideal or best reference objective values

$$O_j^{Ideal} = \max_{i\epsilon m} O_{ij} \tag{25}$$

Step 3: Obtaining the deviation between the $O_j^{Ideal}$ and $O_{ij}$

$$\Delta D_{ij} = \left|O_j^{Ideal} - O_{ij}\right| \quad (26)$$

Step 4: Computation of GRC for each optimal solution

$$GRC_i = \frac{1}{m}\sum_{j=1}^{n}\frac{\Delta\text{min} + \Delta\text{max}}{\Delta D_{ij} + \Delta\text{max}} \quad (27)$$

where, $i$ = index of the number of optimal solutions ($i = 1,2, \dots, m$), $j$ = the index of the number of objectives ($j = 1,2, \dots, n$), $\Delta\text{max} = \text{max}_{i\epsilon m, j\epsilon n}(\Delta D_{ij})$, $\Delta\text{min} = \text{min}_{i\epsilon m, j\epsilon n}(\Delta D_{ij})$.

Based on the concept of GRA, the larger the value of $GRC_i$ the more reliable the optimal solution is. Therefore, the largest value of $GRC_i$ is the recommended best optimal solution from the Pareto optimal solution.

The sustainability of the groundwater withdrawal as proposed in the management model was justified by observing the hydraulic heads at the monitoring locations and by calculating the amount of water entering and leaving the aquifer. Sustainability in terms of groundwater exploitation was evaluated by comparing the depth of water withdrawn from the proposed optimal pumping strategy with the existing pumping rates. Four solutions from the Pareto front were selected for this purpose. Three solutions were taken from the higher, average, and the lower ranges of total production well pumping. The fourth one was the optimal solution proposed as the best optimal solution based on the GRA method. For the optimal solutions, the total depth of water was calculated by considering pumping from both the production and barrier wells. The results are presented in Figure 8.

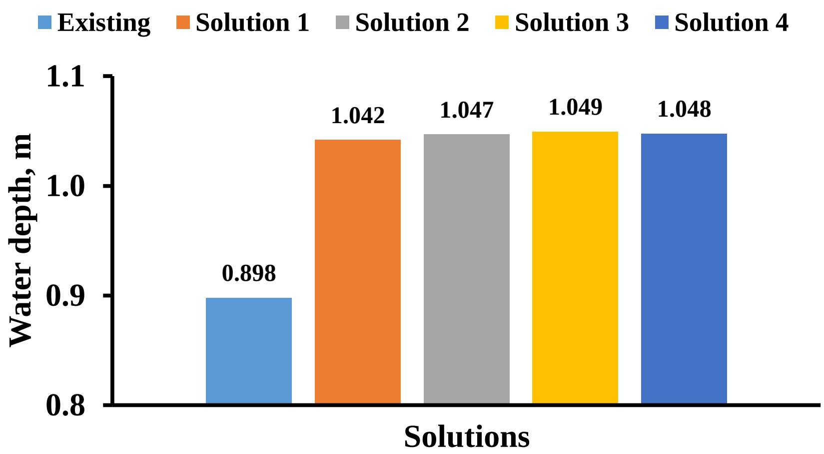


Figure 8. Groundwater abstraction in terms of depth of water (m)

Vertical recharge was assumed to be uniformly distributed over the top layer of the study area. The calibrated recharge of 0.000689 m/day amounted to 150430782 $m^3$/year. This amount of vertical recharge was 84.03% of the total average yearly pumping volume (179032829 $m^3$/year). The deficit amount of water comes into the system through the study area including streams and ocean boundaries, as the groundwater level fluctuates by only a small amount. The groundwater abstraction values obtained as solution of the management model were relatively higher than the existing withdrawals. This extra amount of water abstraction was possible while limiting the salinity to permissible levels due to the barrier wells now included. Although higher than the existing practice, the total optimal abstraction patterns are also safe and sustainable in terms of groundwater exploitation from the aquifer. For the selected optimal solutions, around 72% of the total abstracted groundwater comes from the vertical recharge. More specifically, vertical recharge accounts for

72.41%, 72.06%, 71.91%, and 72.03% of the total groundwater abstraction obtained from the optimal solutions 1, 2, 3, and 4 respectively. The rest of the water enters into the system through the model boundaries. It is expected that the change in pumping patterns should also affect the recharge coming into the aquifer, and therefore should be sustainable. The optimal pumping is again of the same order as the future recharge.

During the validation period (April 2015 to April 2017), the average drop in hydraulic head at the two monitoring locations was 0.062 m (observed by simulating the aquifer processes using the numerical code FEMWATER). Groundwater abstraction caused a 0.898 m of water loss from the system. The drop in hydraulic heads resulting from the proposed optimal groundwater abstraction rates were also estimated from the solution results of the numerical code FEMWATER. The average drop in hydraulic heads obtained by implementing the proposed optimal groundwater abstraction strategies were 0.062 m, 0.062 m, 0.069 m, and 0.067 m for the four optimal solutions, respectively. Water entering the model domain from vertical recharge was 0.754 m during the three years of the management period. Water deficit due to groundwater abstraction during the three years of management period was balanced by the vertical recharge to the aquifer and water entering the system from the model boundary (3 rivers and the seaside) aquifer.

The sustainability in terms of salinity concentration was ascertained by permitting groundwater abstraction within the limits of maximum permissible salinity concentrations at specified monitoring locations. Thus the proposed optimal groundwater abstraction patterns obtained as solutions of the management model was based on satisfying the constraints of maximum permissible salinity concentration at the specified monitoring locations. Sensitivity of the imposed constraints was ascertained by relaxing the constraints and observing the corresponding production and barrier well abstractions. The Pareto optimal front for the new sets of constraints in terms of salinity concentrations is presented in Figure 9.

It is observed from Figure 9 that the new relaxed constraints produced almost the same amount of production well abstraction for a decreased amount of barrier well abstraction. This implies that less amount of barrier well abstraction is required to obtain the same amount of production well abstraction when the maximum permissible salinity concentration is relaxed. In other words, production well abstraction can be increased with the same level of barrier well abstraction. Therefore, based on the guideline of maximum permissible salinity concentrations in the area of interest, the total amount of production and barrier well abstraction can be adjusted.

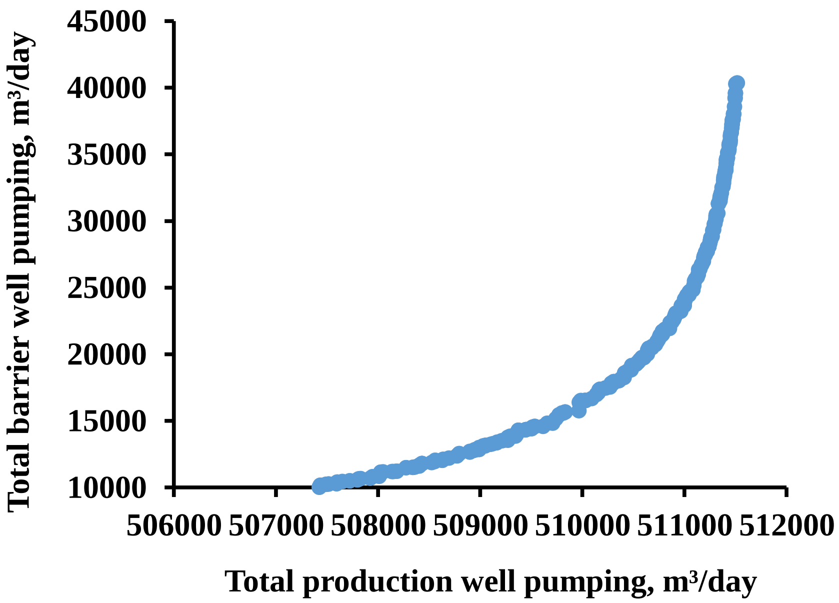

Figure 9. Pareto front with relaxed constraint of maximum permissible salinity concentration

It is noted that by implementing barrier well pumping, the total amount of beneficial pumping from the production wells can be enhanced, while maintaining the maximum permissible salinity concentrations within the permissible limits. Barrier wells aided in an additional groundwater abstraction rate of approximately 30000 $m^3$/day within the safe limit of maximum permissible salinity concentrations. For instance, for solution 1, 6.03% more water abstraction than the existing withdrawal could be achieved by implementing barrier wells. Approximately 0.65 $m^3$/day production well abstraction can be achieved from each $m^3$/day of barrier well abstraction. The values for individual optimal solutions are presented in Table 7. It is observed from Table 7 that the best optimal solution obtained by GRA provided better results than the two randomly selected solutions. However, it produced a slightly worse result than the other randomly selected optimal solution. The proposed GRA might serve as a quick decision making tool to select a relatively better solution from a large number of non-dominated solutions. However, managers can choose the optimal combination of production-barrier well pumping depending on the total demand of water for beneficial purposes.

Barrier wells are located near the seaside boundary of the study area. The seaside boundary is covered by mangrove forest. Therefore, the abstracted water from the barrier well can be efficiently disposed of into the ocean via the mangrove forest. Therefore, the proposed MARS-CEMOGA based saltwater intrusion management methodology is capable of obtaining accurate solutions for optimal groundwater abstractions from a set of production bores and barrier wells in a real world coastal aquifer system.

Table 7. Total amount of water withdrawal in different solutions

| | PW pumping, $m^3$/day | BW pumping, $m^3$/day | Additional water abstraction from PW, $m^3$/day | Additional water abstraction from PW per unit water abstraction from BW |
|---|---|---|---|---|
| Existing | 490500.90 | - | - | - |
| Solution 1 | 520056.38 | 49126.85 | 29555.48 | 0.602 |
| Solution 2 | 522795.23 | 49168.69 | 32294.33 | 0.657 |
| Solution 3 | 523869.32 | 49322.38 | 33368.42 | 0.677 |
| Solution 4 | 523046.40 | 49181.84 | 32545.50 | 0.662 |

## Conclusions

The optimal groundwater abstraction strategy using integrated an S-O approach has been considered an effective measure of controlling saltwater intrusion in coastal aquifers. Although the meta-model based integrated S-O approach has been widely applied in illustrative hypothetical example problems, only a few have focused on saltwater intrusion management in real world applications. This study demonstrates the applicability of the meta-model based integrated S-O approach in solving large-scale real world coastal aquifer management problems. A finite element based 3-D coupled flow and solute transport numerical code, FEMWATER, was utilized to simulate the saltwater intrusion processes in a coastal aquifer system in the Barguna district of southern Bangladesh. Input data for the selected study area of about 598 $km^2$ were collected from different sources. Scarcity and reliability of available data is a challenging issue in implementing regional scale saltwater intrusion models in this location. Therefore, the best possible subjective judgement was used in choosing the data for simulating the aquifer processes. The simulation model was calibrated with respect to hydraulic heads for a period of five years, from April 2010 to April 2014. With the selected hydrogeological parameters obtained from model calibration, the calibrated model was validated for a period of next three years, from April 2015 to April 2017. The calibrated and validated model was then used to develop a saltwater intrusion management model for the study area for a management period of three years, from April 2015 to

April 2017. Computational efficiency in the integrated S-O approach was achieved by replacing the complex numerical simulation model with the properly trained MARS meta-models. The limited evaluation results show that, using a carefully planned groundwater abstraction strategy, it is possible to modify saltwater intrusion processes and help in controlling spatial and temporal saltwater intrusion processes in a real world coastal aquifer study area.

This study utilized a planned pumping strategy from a set of production and barrier abstraction wells. Barrier wells were used as hydraulic control measures to control spatial and temporal distribution of saltwater concentrations. The limited evaluation results revealed that planned pumping strategy along with planned hydraulic control measures can be implemented to develop a saltwater intrusion management model in a realistic regional scale study area. Very limited data were available to calibrate and validate the numerical simulation model, and therefore the evaluation results are limited in scope. Additional reliable data will be required to develop a more acceptable calibrated model for the study area. Only then will the calibrated model be able to be used to prescribe actual implementation of the planned pumping strategy.

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# PREDICTION OF SALTWATER INTRUSION FOR DIFFERENT SCENARIOS OF AQUIFER RECHARGE AND GROUNDWATER EXTRACTION UNDER CHANGING CLIMATE

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## Abstract

Pumping induced saltwater intrusion in coastal aquifers is a challenging problem, due to the increased abstraction of groundwater resources to meet the growing demand for freshwater supplies. The present study intends to evaluate the effects of changing groundwater recharge scenarios as well as anthropogenic activity of enhanced groundwater extraction on the inland progression of saltwater wedge a real world coastal aquifer system in Barguna district of southern Bangladesh. The aquifer processes were simulated by using a calibrated and validated 3-D finite element based combined flow and solute transport numerical model using the code FEMWATER. Simulation was performed with the combination of different scenarios for a period of 50 years. Results demonstrate that the influence of the future scenarios on the salinity intrusion process is remarkable although not significant. It is revealed that salinity intrusion in designated monitoring locations increases with the simulation period. Therefore, an optimal pumping management strategy can be prescribed for the simulated coastal aquifer system by utilizing an integrated simulation-optimization (S-O) approach.


## Introduction

Groundwater is an important source of freshwater supplies to the coastal regions of the world including Bangladesh. An increasing trend in human settlements near the coastal regions inevitably requires more freshwater supplies to meet the demand for agricultural, industrial, and domestic requirements. This growing need of freshwater supplies results in overexploitation of the valuable groundwater resources in coastal areas. Global warming has already triggered drought induced water scarcity in Bangladesh significantly affecting the quantity and quality of groundwater resources, especially in the coastal regions. In fact, over-pumping and climate change induced drought are responsible for accelerating saltwater intrusion processes around the globe including Bangladesh. Therefore, measures should be taken to ensure sustainable management of coastal aquifers for providing safe abstraction of groundwater without causing harm to the aquifer. Assessing the consequences of this anthropogenic activity and its effects on the complex subsurface largely rely on the accurate characterization and simulation of the aquifer processes, and in particular prediction capabilities of future scenarios by the appropriate simulation models. Therefore, this study intends to assess the effects of various scenarios of aquifer recharge and groundwater abstraction on the saltwater intrusion into the aquifer.

In addition, relative sea level rise, providing an additional saline water head at the seaside (Yang et al. 2015), has a reasonable impact in increasing the salinization of the coastal aquifers around the globe (Shrivastava 1998). Although sea level rise can accelerate saltwater intrusion processes in aquifer systems to some extent, the effect of sea level rise is not significant in many parts of the world (Webb and Howard 2011). Nevertheless, the effect of this sea level rise-induced increase in hydraulic heads of the groundwater system is confined within a few kilometers of the coastline and main rivers (Oude Essink et al. 2010). As such, excessive groundwater withdrawal is considered the major cause of saltwater intrusion (Narayan et al. 2007). However, relative sea level rise in combination with the effect of excessive groundwater pumping can exacerbate the already vulnerable coastal aquifers (Langevin and Zygnerski 2013). This study does not consider sea level rise and tidal fluctuations because it is well established that tidal fluctuation-induced head variation has truly little influence on saltwater intrusion processes, and that tidal fluctuation-induced saltwater intrusion has a setback mechanism. However, the present study considers variation of water concentrations in the tidal river, and seasonal fluctuation of head at the upstream end of river. This study adopts a multilayered anisotropic coastal aquifer system in which each individual layer represents different


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materials characterized by varying hydraulic conductivity values in these layers. The flow and transport process considered are also transient and density dependent. This study intends to modelling and prediction of future scenarios of saltwater intrusion processes in a coastal belt of the Southern part of Bangladesh under very limited hydrogeological data availability. A planned spatial and temporal groundwater abstraction strategy with the utilization of negative hydraulic barriers for controlling saltwater intrusion process is also demonstrated.

In sum, this study utilizes different groundwater pumping and recharge scenarios based on projected population growth and climate change scenarios. Climate change induced relative sea level rise and tidal fluctuation have not been included in the simulation process. However, the study evaluated different scenarios of groundwater abstraction and recharge scenarios to assess the aquifer's response with the pumping stress applied to the aquifer in changing climatic scenarios. The resulting effect of these natural and anthropogenic factors on the saltwater intrusion processes is monitored at designated monitoring locations. A properly calibrated and adequately validated FEMWATER model for the study area was used to generate salinity concentrations after 50 years with respect to the accelerated groundwater abstraction and changing groundwater recharge scenarios.

## Materials and Methods

Aquifer processes are simulated using a density dependent finite element-based 3D coupled flow and salt transport numerical simulation model, FEMWATER (Lin et al. 1997). The simulation model generates salinity concentrations at designated monitoring locations using randomized groundwater extraction values as inputs obtained from the Latin Hypercube Sampling (LHS) technique (Pebesma and Heuvelink 1999). The governing equations of the combined flow and salt transport processes are expressed as (Lin et al. 1997):

$$\frac{\rho}{\rho_0} F \frac{\partial h}{\partial t} = \nabla . \left[ K . \left( \nabla h + \frac{\rho}{\rho_0} \nabla z \right) \right] + \frac{\rho}{\rho^*} q \qquad (1)$$

$$F = \alpha' \frac{\theta}{n} + \beta' \theta + n \frac{dS}{dh} \qquad (1)$$

where, $F$ = storage coefficient, $h$ = pressure head, $K$ = hydraulic conductivity tensor, $z$ = potential head, $q$ = a source or a sink, $\rho$ = water density at chemical concentration $C$, $\rho_0$ = referenced water density at zero chemical concentration, $\rho^*$= density of injection fluid or that of the withdrawn water, $\theta$ = moisture content, $\alpha'$ = modified compressibility of water, $\beta'$ = modified compressibility of the medium, $n$ = porosity, $S$ = saturation.

The hydraulic conductivity tensor, $K$ is represented by

$$K = \frac{\rho g}{\mu} k = \frac{(\rho/\rho_0)}{\mu/\mu_0} \frac{\rho_0 g}{\mu_0} k_s k_r = \frac{\rho/\rho_0}{\mu/\mu_0} k_{so} k_r \qquad (2)$$

where, $\mu$ = dynamic viscosity of water at chemical concentration $C$, $\mu_0$ = reference dynamic viscosity at zero chemical concentration, $k_s$ = saturated permeability tensor, $k_r$ = relative permeability or relative hydraulic conductivity, $k_{so}$ = referenced saturated conductivity tensor.

Both the dynamic viscosity and density of water vary with the chemical concentration. They take the form of the following two equations

$$\frac{\rho}{\rho_0} = a_1 + a_2 C + a_3 C^2 + a_4 C^3 \qquad (3)$$

$$\frac{\mu}{\mu_0} = a_5 + a_6 C + a_7 C^2 + a_8 C^3 \quad (4)$$

where, $a_1, a_{2,\dots,} a_8$ indicates the coefficients that defines the dependence of density and viscosity of water on chemical concentration; and $C$ represents the chemical concentration.

The Darcy velocity term $V$ is given by the following equation

$$V = -K.\left(\frac{\rho_0}{\rho}\nabla h + \nabla z\right) \quad (5)$$

The 3-D solute transport equation is expressed as

$$\theta\frac{\partial C}{\partial t} + \rho_b\frac{\partial S}{\partial t} + V.\nabla \mathrm{C} - \nabla.(\theta D.\nabla \mathrm{C})$$

$$= -\left(\alpha'\frac{\partial h}{\partial t} + \lambda\right)(\theta C + \rho_b S) - (\theta K_w C + \rho_b K_s S) \quad (6)$$

$$+m - \frac{\rho^*}{\rho}qC + \left(F\frac{\partial h}{\partial t} + \frac{\rho_0}{\rho}V.\nabla\left(\frac{\rho}{\rho_0}\right) - \frac{\partial C}{\partial t}\right)C$$

where, $\rho_b$ = bulk density of the medium, $C$ = material concentration in aqueous phase, $S$ = material concentration in adsorbed phase, $t$ = time, $V$ = discharge, $\nabla$ = del operator, $D$ = Dispersion coefficient tensor, $\lambda$ = decay constant, $M = qC_m$ = artificial mass rate, $q$ = source rate of water, $C_m$ = material concentration in the source, $K_w$ = first order biodegradation rate constant through dissolved phase, $K_s$ = first order biodegradation rate through adsorbed phase, $K_d$ = distribution coefficient.

The dispersion coefficient tensor $D$ in equation (6) is expressed as

$$\theta D = a_T|V|\delta + (a_L - a_T)\frac{VV}{|V|} + a_m\theta\tau\delta \quad (7)$$

where, $|V|$ = magnitude of $V$, $\delta$ = Kronecker delta tensor, $a_T$ = lateral dispersivity, $a_L$ = longitudinal dispersivity, $a_m$ = molecular diffusion coefficient, and $\tau$ = tortuosity.

***Study area***

The study area is located in Barguna district, one of the coastal districts of Bangladesh. It is located in the southern part of Bangladesh, lying between 21º48′ and 22º29′ north latitudes and between 89º52′ and 90º22′ east longitudes, and is also within the tropics. The land area is nearly flat, having rivers and estuarine creeks with regular low and high tides. The Barguna district belongs to the Gangetics tidal floodplain that is highly susceptible to storms and tidal flooding. The coastal aquifer is contaminated by salinity intrusion resulting from large amounts of extraction. The study area consists of two upazillas (administrative units) in the Barguna district: Patharghata (258.63 $km^2$) and Barguna sadar (339.54 $km^2$). The southern part of the study area is surrounded by the mangrove forest and the Bay of Bengal. The aerial map of the study area is presented in Figure 1.

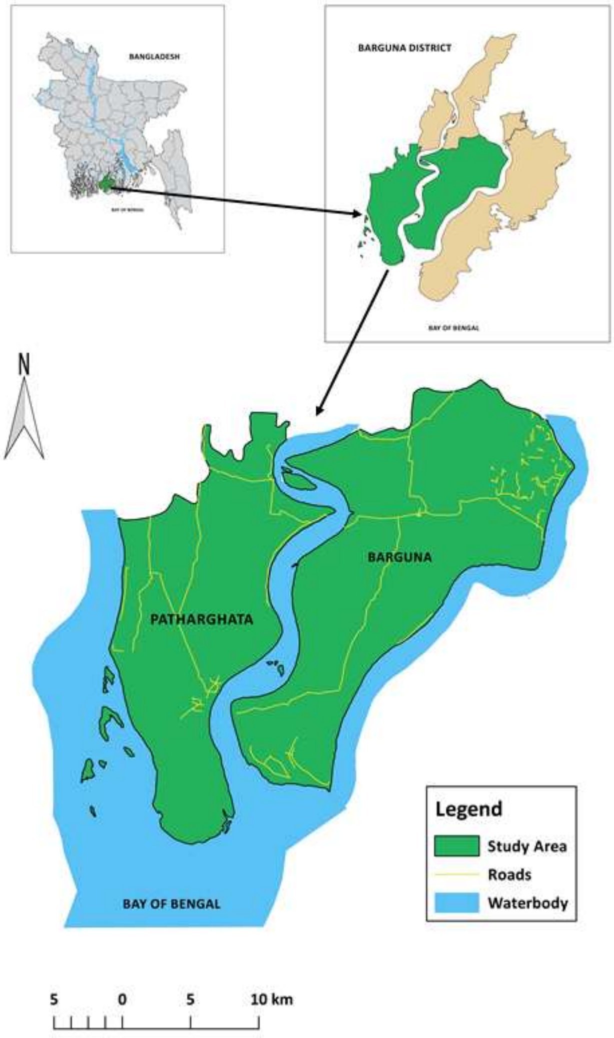


Figure 1. Location and aerial map of the study area

During the wet monsoon season, water enters the study area through recharge from rainfall and the water discharges into the river systems (Faneca Sanchez et al., 2015). In contrast, the study area receives water through infiltration from the rivers during the dry cold seasons, the quality of groundwater depending on the salt concentration of the surface water. Groundwater abstraction has very little influence (only 4%) on the water balance of the study area in the wet monsoon season. In the dry season, groundwater abstraction accounts for about 50-70% of groundwater leaving the study area (Faneca Sanchez et al., 2015). Many wells are in use in each village, each shared by a single family or a group of several families, and 97% of the rural population uses groundwater for its water supply (Kinniburgh et al., 2003). Deep tube well depths range between 60-100 m whereas shallow tube well depths range between 10-60 m (Kinniburgh and Smedley, 2001; Mondal and Saleh, 2003).

## Modelling of saltwater intrusion processes

### *Model development*

The major difficulty in developing a regional scale saltwater intrusion model is the scarcity of reliable data for hydrogeological parameters and groundwater use in the area. Data from various sources were utilized in the model development, based on the best possible subjective judgement. Hydraulic head data for a period of eight years (April 2010 to April 2017) were collected from the website of the Processing and Flood Forecasting Circle of Bangladesh Water Development Board (BWDB) (Bangladesh Water Development Board. Processing and Flood Forecasting Circle, 2018). Two hydraulic head values were obtained for the study area (one from each upazilla). The observation well at Patharghata upazilla is located at 22° 11' 8" north latitude and 89° 59' 21" east longitude. The other observation well at Barguna sadar upazilla is located at 22° 9' 26" north latitude and 90° 6' 2"east longitude. Surface water level and salinity data were collected from the website of BWDB (Bangladesh Water Development Board. Processing and Flood Forecasting Circle, 2018). Based on the data, a specified head was assigned at the upstream end of the river and interpolated over the lengths of the river. A constant concentration of river water salinity was assumed. There are three distinct seasons in Bangladesh: 1) a cold dry winter from November to February, 2) a humid hot summer from March to May and 3) a cool rainy monsoon season from June to October. These seasonal variations only affect the top layers of the aquifer (Faneca Sanchez et al., 2015). Therefore, the average values of the parameters for these three different seasons were used in this study.

Previous studies in the Bengal Delta modelled a very large area (Faneca Sanchez et al., 2015; Michael and Voss, 2009) by assuming groundwater abstraction per unit area of the model domain. The withdrawals were distributed based on estimates made for each administrative unit. Of note, it is difficult to represent pumping in the model domain as individual wells because of the large number of unreported wells and the large scale of the study area. However, the main aim of this study was to prescribe optimal groundwater abstraction patterns to control saltwater intrusion. In addition, the implementation of hydraulic control measures in the form of barrier abstraction wells was also used as a measure of salinity control. Therefore, the exact location of the point pumping was approximated in the present study based on the land use pattern of the study area. In conformance with the total water abstraction and for simplicity in the model, total water abstraction was distributed among the individual wells during the calibration and validation processes. Groundwater abstractions were calculated from domestic, industrial, and agricultural water use. Total domestic and industrial pumping rates were based on estimates of population and per capita water consumption rates (Michael and Voss, 2009). Total domestic and industrial demand were taken as 50 l/day/capita (Faneca Sanchez et al., 2015; Michael and Voss, 2009) and assumed constant throughout the year. Total population for the study area were obtained by using data from the population census of the district statistics of Bangladesh (Bangladesh Bureau of Statistics (BBS), 2013). A population growth rate 2.09% per year (Michael and Voss, 2009) was used to calculate the number of population in subsequent years of simulation. Total domestic and industrial water abstraction was calculated from the following equation

$$Q_{domestic+industrial}(m^3/day) = Population\ size \times Annual\ growth\ rate \times Per\ capita\ water\ demand \tag{22}$$

The amount of water abstraction for irrigation purposes was computed from the total irrigated portion of the study area multiplied by the quantity of applied water to the irrigated area during the crop growing season (Michael and Voss, 2009). Total irrigated area in the study area was obtained from the district statistics for Barguna district (Bangladesh Bureau of Statistics (BBS), 2013). The total irrigated area was multiplied by an abstraction rate of 1 m/pumping season/m$^2$ of irrigated area (Harvey et al., 2006).

The type and thickness of aquifer material layers were chosen in accordance with the lithological data of the study area. It is noted that up to 300m depth of the study area falls under alluvium soil type composed mainly of clay, silt, sand, and occasional gravel (Faneca Sanchez et al., 2015). As most of the physical processes are occurred in the first few meters of the aquifer, an aquifer thickness of 150 m was chosen. The total thickness of the aquifer was divided into four layers of materials. First layer below the ground surface belongs to sandy silt with a thickness of 40 m, followed by a layer of sandy loam with 50 m thickness, followed by a soil type of sand with a thickness of 40 m. The bottom layer was specified as sandy clay with a thickness of 20 m. An average value of hydraulic conductivity was assigned to each model layer. The aquifer material within each model layer was assumed homogeneous, only vertical heterogeneity in terms of hydraulic conductivity was considered. The hydraulic conductivity values used in this study were in accordance with previous studies conducted in the Bengal Delta (Faneca Sanchez et al., 2015; Michael and Voss, 2009). An anisotropy ratio ($kx/ky$) = 2.0 was used, where $kx$ represents the horizontal hydraulic conductivity in the $X$-direction. $ky$ is the horizontal hydraulic conductivity in the $Y$-direction. $kz$ is the vertical hydraulic conductivity in the $Z$-direction. The value of $kz$ was taken as one tenth of the hydraulic conductivity values in the $X$-direction. The 3-D view of the model domain with finite element meshes is illustrated in Figure 2.

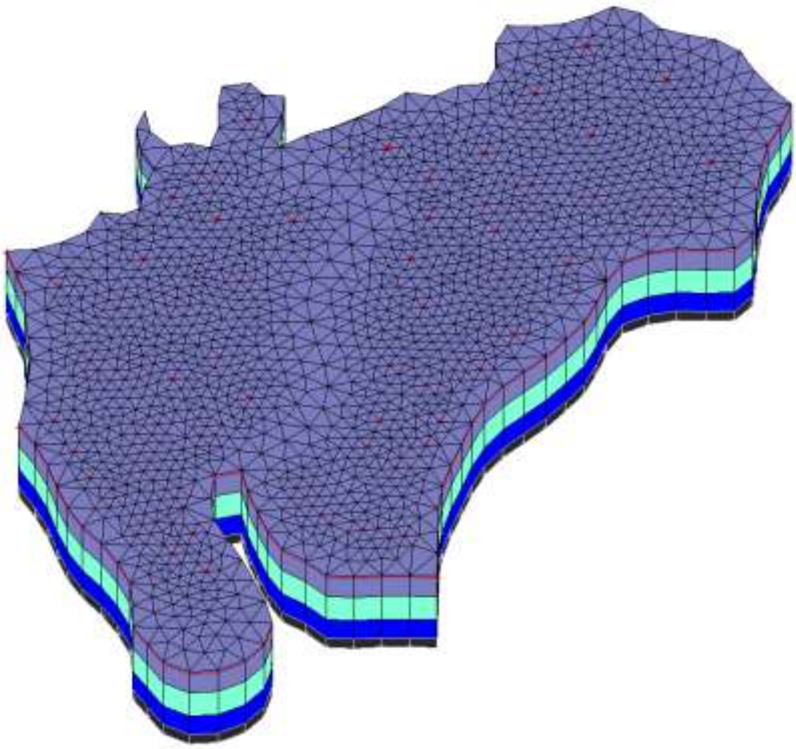

Figure 2. Three dimensional view of the study area

The study area is bounded by the Bay of Bengal in the southern side, Burishwar River in the eastern side, and Haringhata River in the western side. A river named Bishkhali is flowing in the middle part of the study area separating the two administrative upazillas. The Northern boundary is the administrative boundary, which was specified as the no flow boundary. Although it is very difficult to conclude that the northern boundary is a no flow boundary, the no flow boundary condition was assumed based on the consideration that the study area has a negligible hydraulic gradient (around 1:20000) in the vicinity of this boundary. Therefore, lateral movement of groundwater across this boundary, as shown in Figure 1, can be considered as negligible (Faneca Sanchez et al., 2015). Therefore, for modelling purposes, this northern boundary as shown in Figure 1 was assumed as a no flow boundary. In addition, the northern boundary is relatively far away from the sea face boundary. Moreover, the calibration-validation process did not show that it was an unreasonable assumption. The seaside boundary was assigned as a constant head and constant concentration boundary. Constant head and constant concentration values in the seaside boundary were specified as zero (MSL) and 35000 mg/l, respectively. The upstream ends of the rivers were assigned specified head values that varied linearly along the stream and ended at zero meter at the seaside boundary. Specified heads of 0.8 m, 0.86 m, and 0.70 m were assigned at the upstream ends of Haringhata, Bishkhali, and Burishwar Rivers, respectively. The tidal river salinity concentrations were specified as 10000 mg/l and assumed to be constant throughout the simulation period. The fluid properties used in this study are presented in Table 1.

Table 1. Fluid properties

| Parameters | Units | Values |
|---|---|---|
| Density of freshwater | $Kg/m^3$ | 1000 |
| Density of seawater | $Kg/m^3$ | 1028 |
| Dynamic viscosity of water | Kg/m–day | 131.328 |
| Compressibility of water | $m–day^2/kg$ | $6.69796 \times 10^{-20}$ |
| Density reference ratio | dimensionless | 0.025 |

A plan view of the study area with boundaries and wells is shown in Figure 3. In Figure 3, the production wells, barrier wells, and monitoring locations are indicated by P1-P43, B1-B13, and M1-M16, respectively. For calibration and validation purposes, barrier well pumping was not considered and the hydraulic heads were observed at monitoring locations M1 and M2. Once proper calibration and validation were performed, barrier extraction wells were introduced as the hydraulic control measures of the saltwater intrusion processes. Moreover, an additional 14 monitoring locations were used to monitor salinity concentrations for developing the saltwater intrusion management model for the study area.

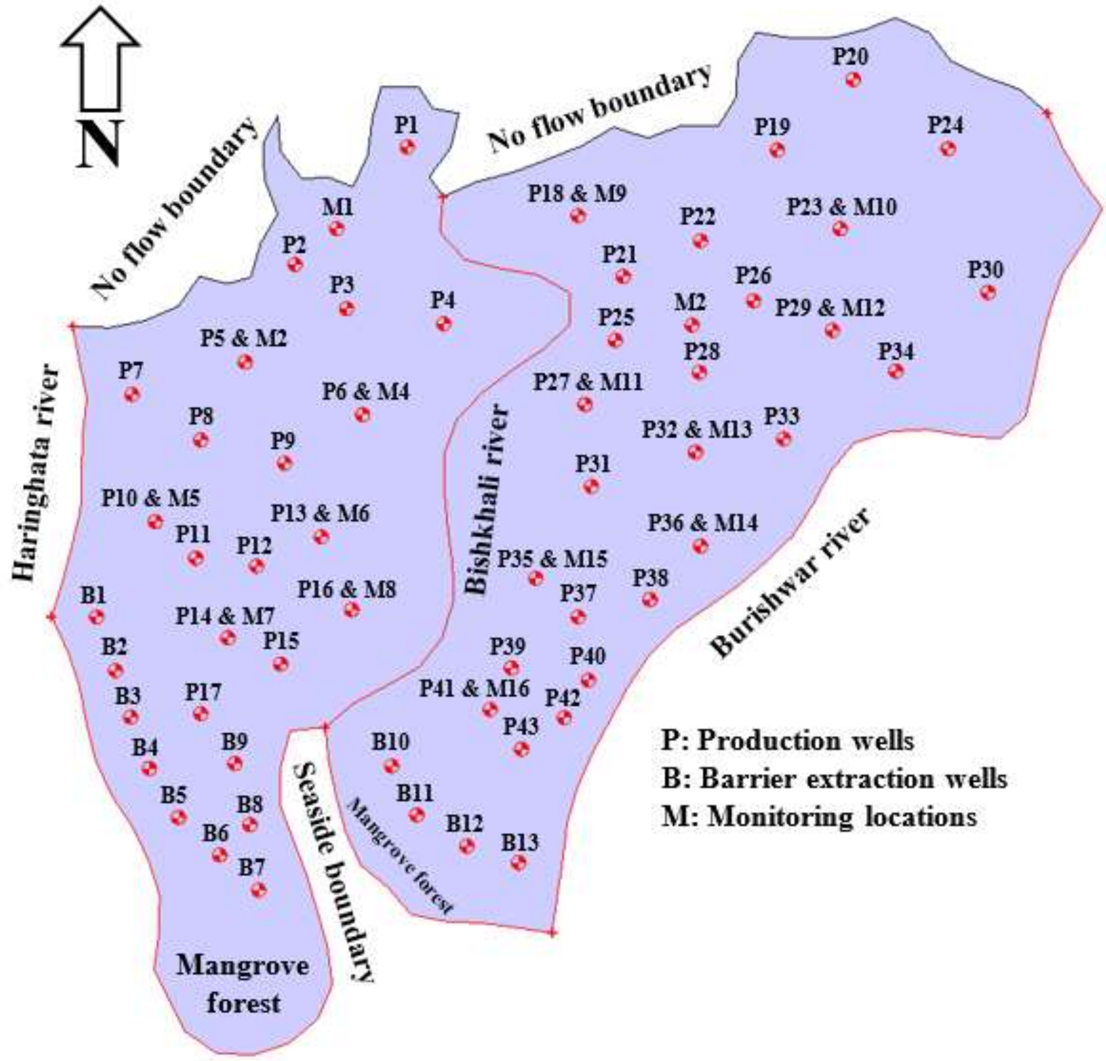


Figure 3. Plan view of the study area showing the boundaries and wells

***Mesh dependency test***

The accuracy of numerical simulation models often depends on the size of the finite elements. However, finer mesh size is associated with additional computational requirements. Therefore, modelling should be performed by maintaining a balance between accuracy and computational requirement. For this, the mesh dependency of the simulated hydraulic heads was determined by conducting numerical experiments, utilizing element sizes of 600m, 800m, 1000m, and 1200m. The simulation was performed for a period of 10 years, with a constant groundwater abstraction rate of 4000 $m^3$/day from each of the 43 production wells. Hydraulic heads and the time required for simulating the aquifer processes at the end of the simulation period were computed at two monitoring locations M1 and M2, and are presented in Table 2. Table 2 shows that the computed hydraulic heads did not vary significantly when different element sizes were used. However, there was a substantial increase in simulation times with the increase in element size. Considering the computation time and accuracy of simulation, an element size of 1200 m was used in the present study.

Table 2. Hydraulic heads and simulation times with different element sizes

| Element size, m | Hydraulic heads, m | | Simulation time, min |
|---|---|---|---|
| | Patharghata (M1) | Barguna Sadar (M2) | |

| | | | |
|---|---|---|---|
| 1200 | 2.823 | 2.598 | 13.05 |
| 1000 | 2.825 | 2.597 | 18.57 |
| 800 | 2.826 | 2.598 | 29.58 |
| 600 | 2.825 | 2.598 | 47.95 |

*Model calibration*

The calibration process was initiated from a steady state condition of the hydraulic heads in the finite element nodes of the model domain. To achieve this condition, the transient simulation model was run for 80 years (April 1930 to April 2009). The simulation was performed in stages with an interval of 10 years. An average value of pumping was used during this simulation period. Outputs at the end of the 10$^{th}$ year's simulation were used as initial conditions for the subsequent intervals of 10 years' period. The process was continued until April 2009, when a stable condition with respect to hydraulic head was achieved. These hydraulic head values at different nodes of the model domain were used as initial conditions for the calibration process. The calibration was performed from a period of five years (from April 2010 to April 2014). The hydraulic heads were monitored at the designated monitoring locations (M1 and M2) on April 2010, April 2011, April 2012, April 2013, and April 2014. Recharge and hydraulic conductivity values were adjusted to obtain the hydraulic heads closer to the actual hydraulic heads in the monitoring locations M1 and M2. Table 3 presents major parameter values used in the calibrated model.

Table 3. Parameter values of the calibrated model

| Parameters | Values | Units |
|---|---|---|
| Hydraulic conductivity in X-direction for soil layer 1 | 4 | m/day |
| Hydraulic conductivity in X-direction for soil layer 2 | 10 | m/day |
| Hydraulic conductivity in X-direction for soil layer 3 | 15 | m/day |
| Hydraulic conductivity in X-direction for soil layer 4 | 8 | m/day |
| Aquifer recharge applied on the top soil layer | 0.000689 | m/day |
| Longitudinal dispersivity | 80 | m |
| Lateral dispersivity | 30 | m |
| Molecular diffusion coefficient | 0.69 | $m^2$/day |

Actual and simulated hydraulic heads at two upazillas (M1 and M2 in Figure 3) during the calibration process are presented in Figure 4.

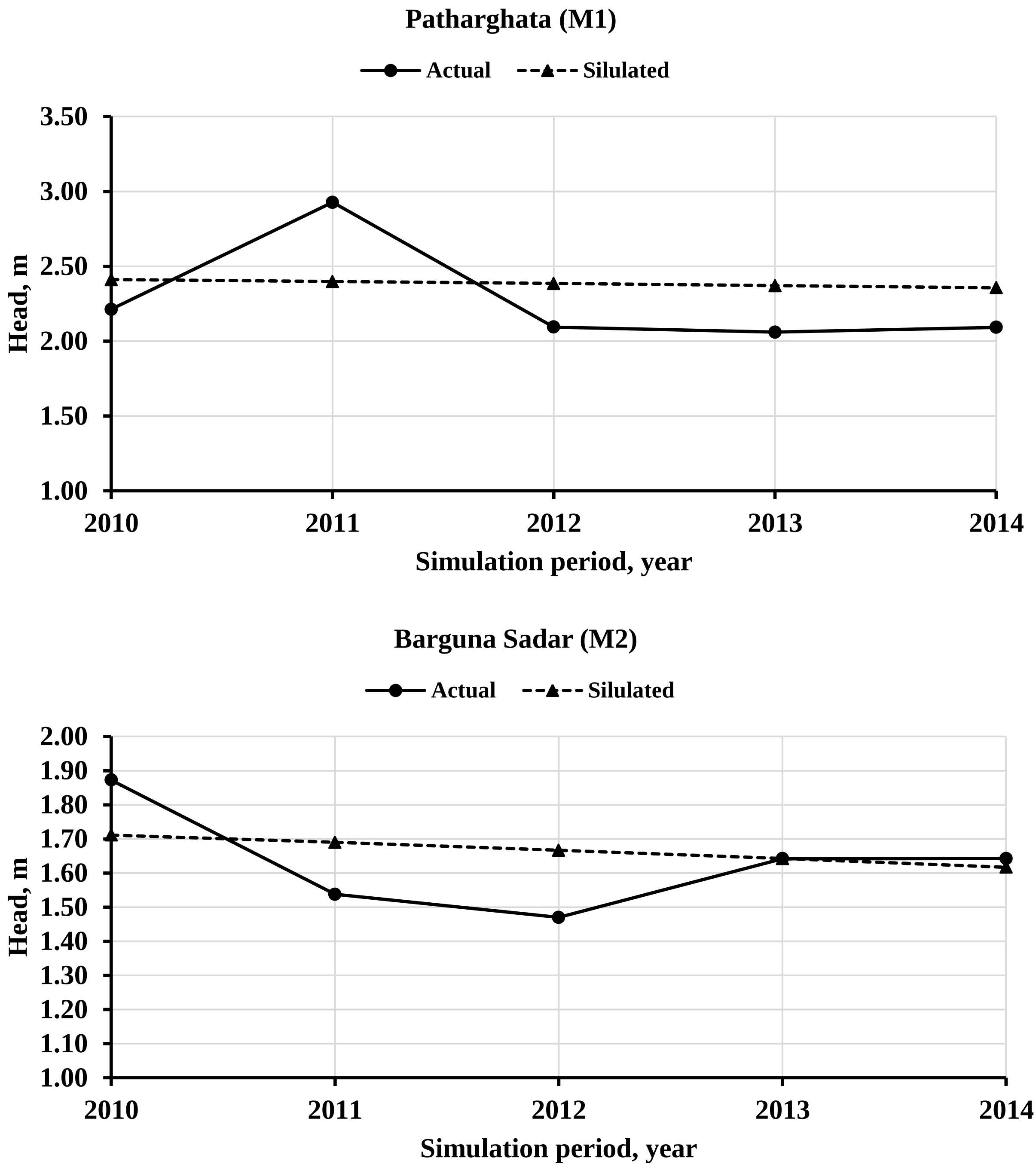


Figure 4. Actual and simulated hydraulic heads at two upazillas during the calibration process.

The calibrated model was then validated for the next three years from April 2015 to April 2017. Outputs in terms of hydraulic heads on April 2014 were used as the initial condition for the simulation of the validation period. The model boundary conditions remained same as the calibrated model. At the end of the simulation period, the hydraulic heads were monitored at monitoring locations M1 and M2 in April 2015, April 2016, and in April 2017. Hydraulic heads during the validation process is presented in Figure 5.

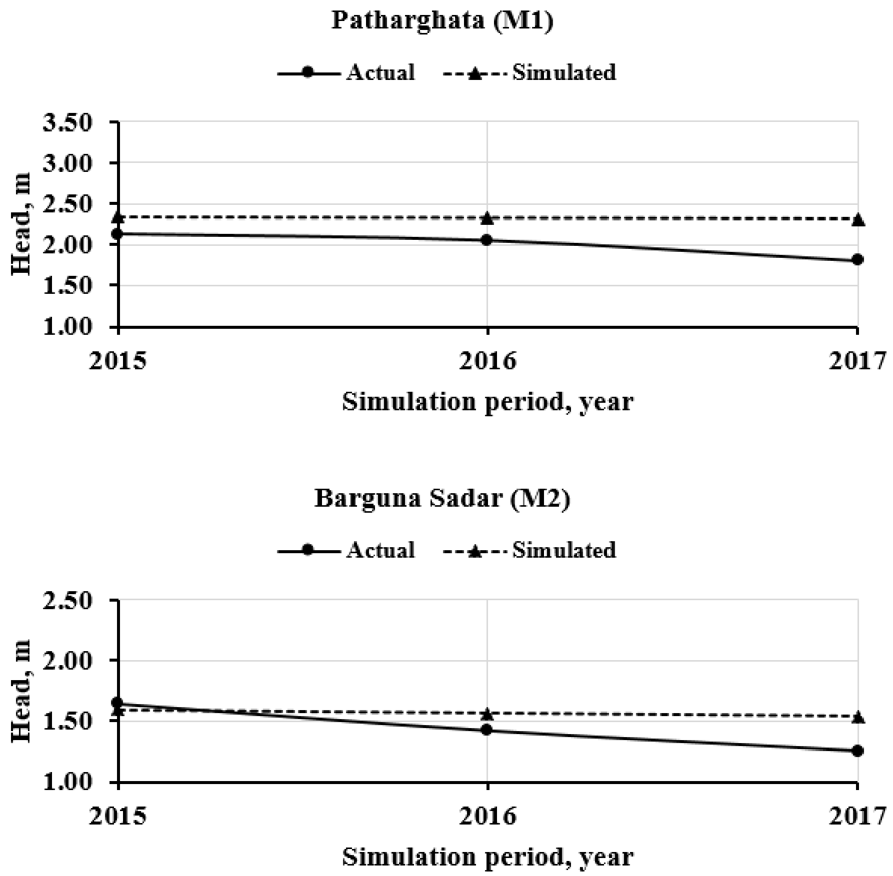


Figure 5. Actual and simulated hydraulic heads at two upazillas during the validation period.

The calibration and validation processes were performed by using a uniform time step of 5 days' interval. A smaller time step is associated with higher computational time requirements and vice versa. Computational time is an issue in situations where multiple simulations of the aquifer processes with different sets of transient pumping values are required to train and test a meta-model for using in an integrated S-O approach. Therefore, a sensitivity analysis was performed to evaluate the effects of time steps of simulation on the computed hydraulic heads. Time steps of 1 day, 5 days, 10 days, and 73 days were used to simulate the hydraulic heads during the calibration periods from April 2010 to April 2014. The results are presented in Table 4.

Table 4. Sensitivity of simulation time steps to simulated hydraulic heads

| Calibration period | Hydraulic heads, m | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Patharghata | | | | Barguna Sadar | | | |
| | 1 day | 5 days | 10 days | 73 days | 1 day | 5 days | 10 days | 73 days |
| 2010 | 2.41155 | 2.41105 | 2.41121 | 2.41094 | 1.71220 | 1.71135 | 1.71163 | 1.71120 |
| 2011 | 2.39968 | 2.39483 | 2.39844 | 2.39858 | 1.69179 | 1.68964 | 1.68968 | 1.68995 |
| 2012 | 2.38669 | 2.38463 | 2.38484 | 2.38503 | 1.66941 | 1.66588 | 1.66625 | 1.66661 |
| 2013 | 2.37317 | 2.37035 | 2.37030 | 2.37094 | 1.64606 | 1.64120 | 1.64112 | 1.64227 |
| 2014 | 2.35933 | 2.35583 | 2.35581 | 2.35645 | 1.62204 | 1.61599 | 1.61597 | 1.61712 |

Table 4 shows that the estimates of hydraulic heads did not differ substantially among different time steps during the calibration periods. However, a considerable amount of computational efficiency was achieved when a simulation time step of 73 days was used. Time taken to simulate the aquifer processes for the time steps of 1 day, 5 days, 10 days, and 73 days were 14.61 min, 4.82 min, 3.17 min, and 0.95 min, respectively. Therefore, simulation time steps of 73 days were used in the multiple simulations with different transient pumping values. These multiple simulations were used to generate input-output training patterns for training of the meta-model.

After proper calibration and validation has been ensured, the calibrated and validated model was used to predict future salinity concentrations within the aquifer subjected to enhanced groundwater abstraction and varying recharge. Future groundwater extraction pattern was generated using LHS technique from 43 production and 13 barrier wells for a simulation period of 50 years. During these periods, groundwater extraction is assumed to be increased to meet the increasing water demands in different sectors, with agriculture being considered as the highest water users. A spatiotemporal pumping pattern was applied in which the pumping varies spatially (among various wells) and temporally (during the simulation period).

Figure 6 illustrates the used recharge values which are applied uniformly over the top aquifer layer. The recharge values are obtained from random sampling using LHS approach. As opposed to groundwater pumping values, the recharge values are randomly selected to accommodate the variability and uncertainty in climatic parameters.

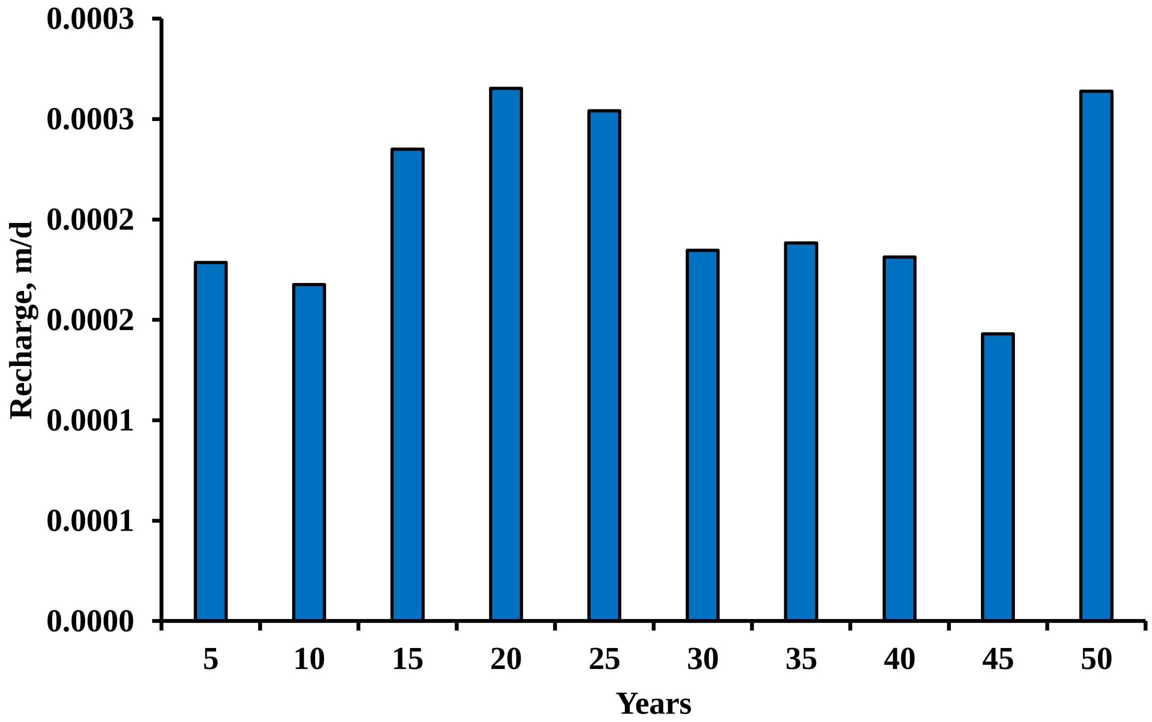


Figure 6. Varying groundwater recharge due to climatic variabilities during successive simulation periods.

## Results and Discussion

To demonstrate the effects of increased groundwater extraction, varying aquifer recharge, river water concentration, and seasonal variation of river water stage on the migration of salt plume, a continuous simulation for a period of 50 years was performed. Figure 7 demonstrates the inland movements of saltwater plume over time. Compared to the simulation results after 5 years (Figure 7 a), a remarkable increase in saltwater wedge movement was observed in the result of simulation for a period of 50 years (Figure 7 b). Saltwater intrusion is observed to be more pronounced when performed a 50 year simulation with varying recharge and increased groundwater abstraction scenarios. Figure 8 presents a 3D view of the saltwater intrusion processes under changing groundwater parameters.

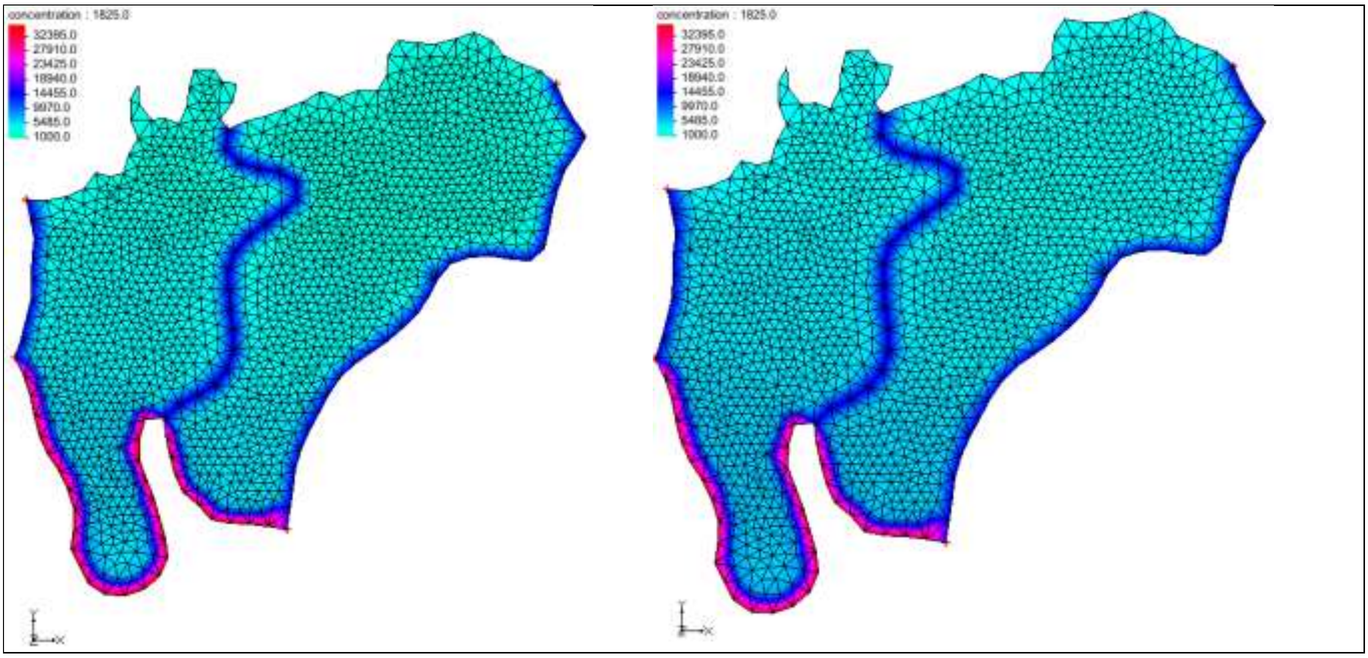


Figure 7. Resulting saltwater concentrations in the aquifer after (a) 5 and (b) 50 years.

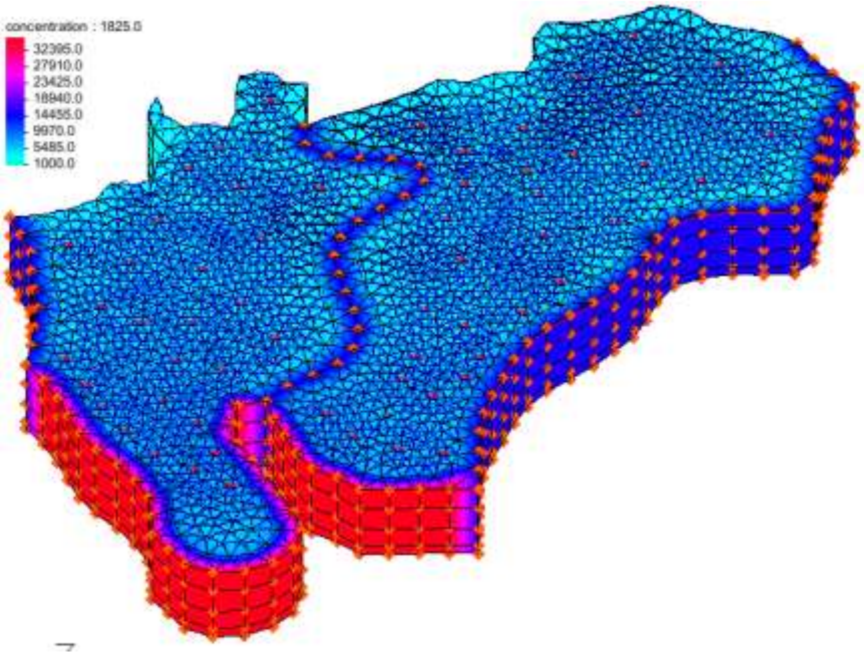


Figure 8. Salinity intrusion in the aquifer after 50 years: three-dimensional view.

Figures 9, 10, 11, and 12 present the salinity concentrations at individual monitoring locations during successive simulation periods. It is observed from Figures 9, 10, 11, and 12 that salinity concentrations increase with the increased pumping stress applied to the aquifer although the magnitude varies. It is also observed that salinity concentrations are more evident at monitoring points located close to the seaside bopundary than others located more inland. Nevertheless, increased groundwater extraction in combination with varying recharge scenarios inevetably increase the extent of salinity intrusion in the aquifer as monitored in various monitoring locations placed at different parts of the aquifer.

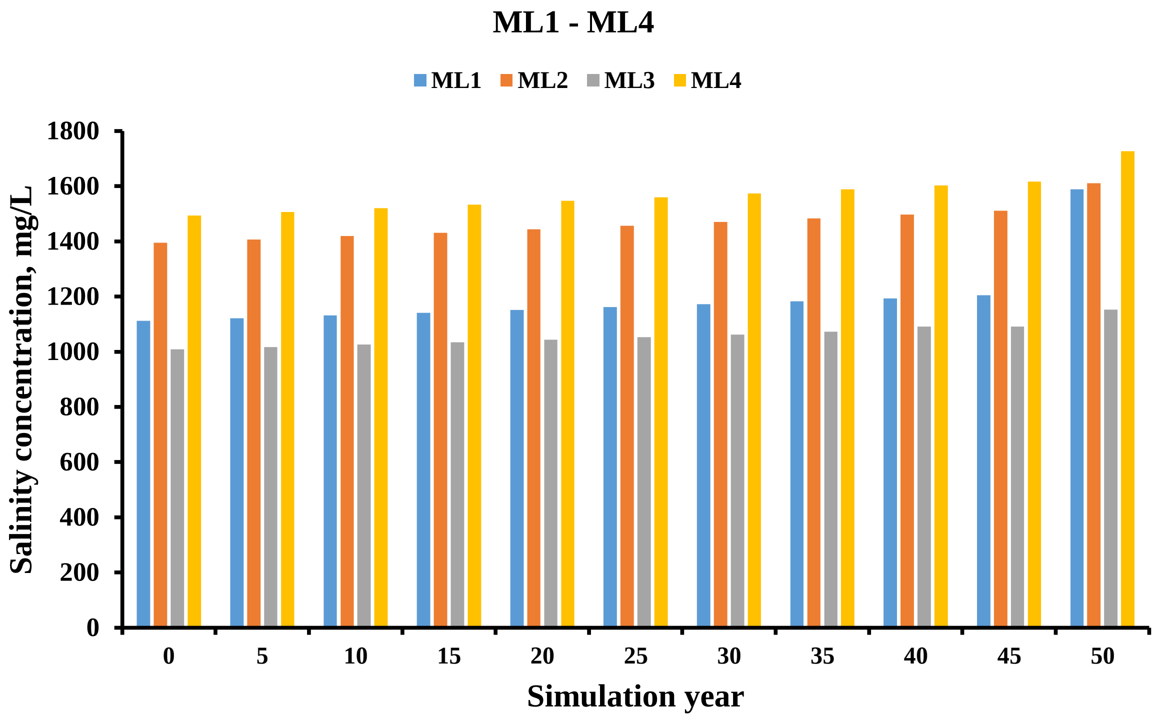


Figure 9. Observed salinity concentrations at the monitoring locations ML1 – ML4 during the simulation period of 50 years

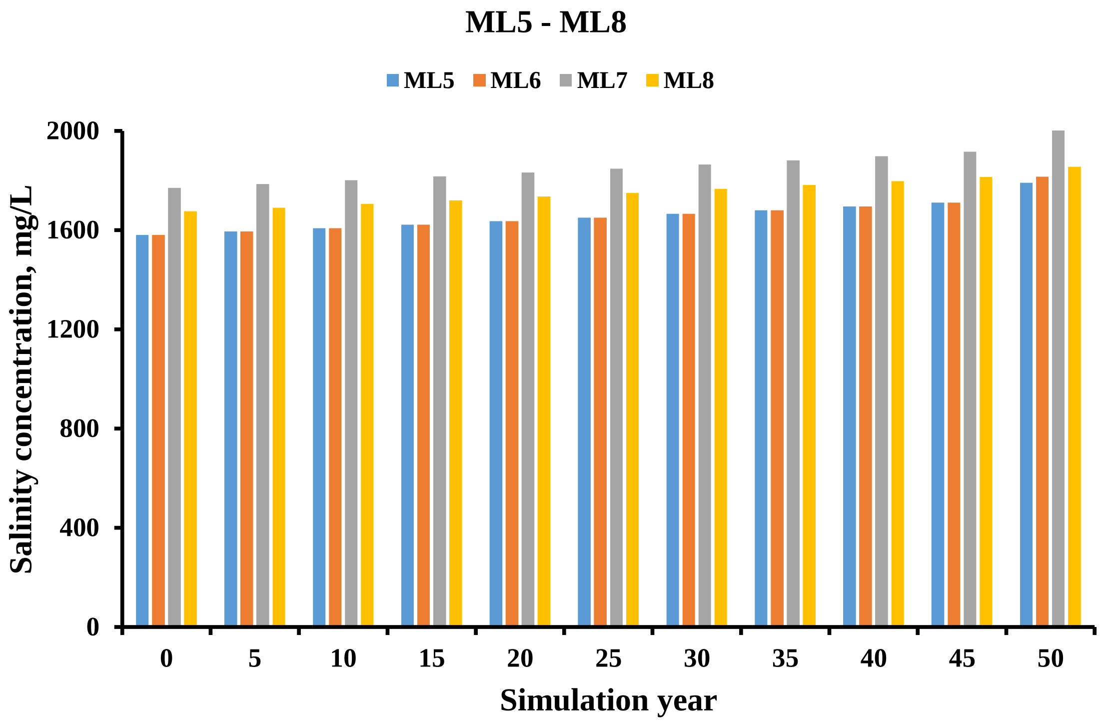


Figure 10. Observed salinity concentrations at the monitoring locations ML5 – ML8 during the simulation period of 50 years

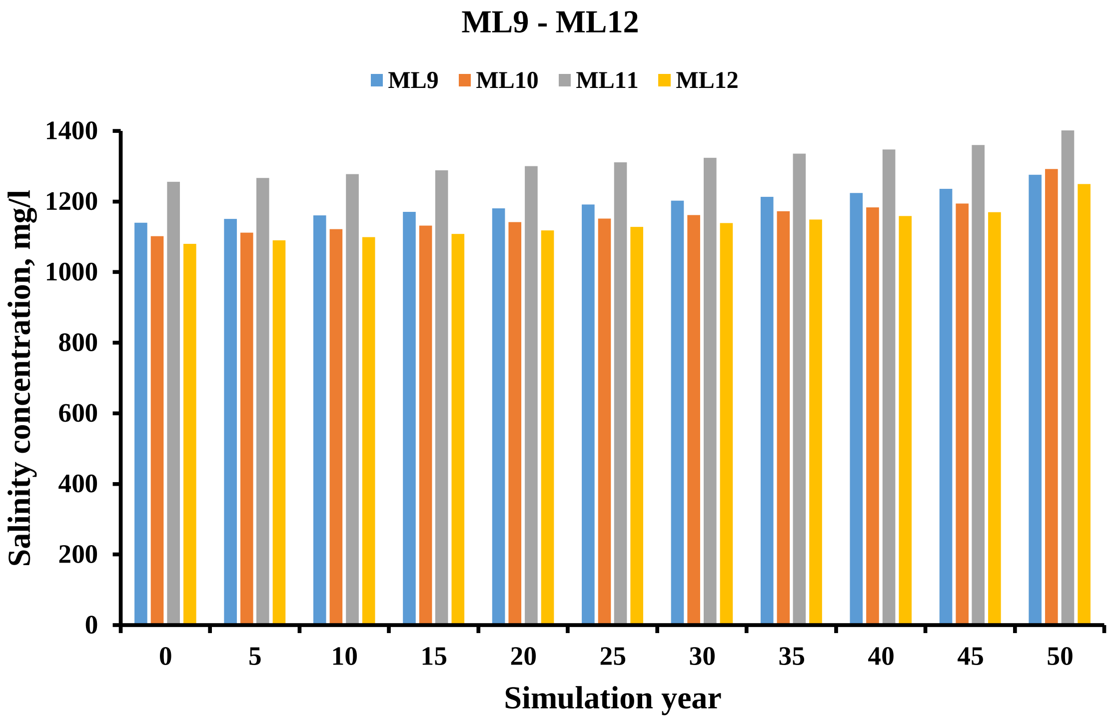


Figure 11. Observed salinity concentrations at the monitoring locations ML9 – ML12 during the simulation period of 50 years

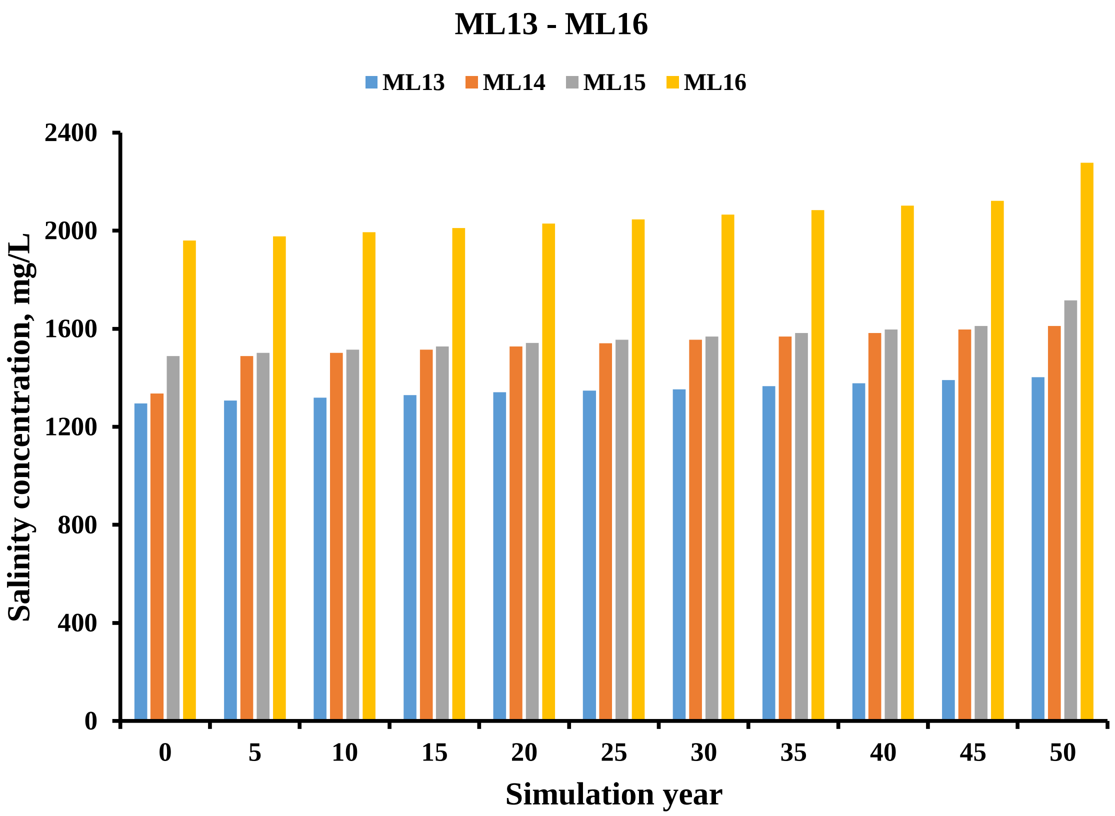


Figure 12. Observed salinity concentrations at the monitoring locations ML13 – ML16 during the simulation period of 50 years

## Conclusion

Coastal aquifers are susceptible to saltwater intrusion arising from a multitude of factors including overpumping of groundwater resources, climate change induced sea level rise and reduced recharge. This study demonstrates the potential impact of these natural and anthropogenic factors in the salinity intrusion processes of a coastal aquifer system in the southern Bangladesh. Results reveal the remarkable impact of these future scenarios on the saltwater intrusion phenomena as evedenced by the increased salnity concentrations at the designated monitoring locations over the simulation period. The findings of this study is of great importance to developing a meaningful saltwater intrusion management strategy.

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## MONITORING OF GROUND WATER LEVEL AT DIFFERENT BARI STATIONS

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### Abstract

This study was conducted at the research fields of Irrigation and water Management Division (IWM), RARS, Rahmatpur, Barisal, and RARS Ishurdi, Pabna of Bangladesh Agricultural Research Institute (BARI) during 2019-2020, 2020-2021 and 2021-2022. Two observation wells were installed at IWM Division, BARI, Bazipur and RARS Rahmatpur, Barishal for regular monitoring of groundwater level fluctuations. On the other hand, an existing well was used to monitor groundwater level fluctuations at RARS, Ishurdi, Pabna. In IWM Division research field, a boring depth of 210 ft. with a strainer length 20 ft. was found sufficient for the purpose of groundwater level monitoring. At RARS, Rahmatpur, Barishal, the boring depth was 860 ft with a strainer length of 20 ft. The existing well at RARS Ishurdi station had a boring depth of 120 ft with a strainer length of 20 ft. It is noted that the boring depth and the strainer length depends on the underlying water bearing strata. The installation of observation wells at other stations is ongoing. The monitoring of groundwater level fluctuations in the installed observation well at IWM Division and RARS, Eahmatpr, Barishal as well as the in the existing well at RARS Ishurdi has been continuing.

### Introduction

Variations in water storage, including surface water, snow and ice, soil moisture, and groundwater, are essential for understanding a wide range of hydrologic, climatic, and ecologic processes and are important for water resources and agricultural management. Water scarcity is a global concern, with an estimated 1.1 billion people lacking access to clean water (Salman, 2005). Increasing demand for water requires more accurate information needed on water resources. While monitoring networks for precipitation and rivers exist in most regions, monitoring of subsurface water reservoirs (soil moisture and groundwater) is inadequate. However, groundwater represents a much larger fraction (~30%) of global fresh water resources than rivers (~0.006%) (Dingman, 2002). In addition, depletion of groundwater resources has increased substantially in the last several decades, particularly in places where groundwater- based irrigation has expanded (Scanlon et al., 2007). However, monitoring of groundwater storage in Bangladesh is extremely limited. Lack of information on groundwater storage changes inhibits development and execution of effective water management plans. Many countries with severe groundwater depletion problems have limited information on spatial and temporal variability in groundwater storage (Strassberg et al., 2009), as monitoring networks are generally limited and it is difficult to regionalize point- based measurements. To improve water resources management, it is critical to develop monitoring systems that provide accurate and timely information on the status of water reservoirs, including water in soil and aquifers. Therefore, an experiment was proposed with a view to meet the following objectives:

1) Installation of observation well at different BARI stations
2) Regular monitoring of groundwater level at 7 days' interval
3) To determine the depletion of groundwater level

### Materials and Methods

The evaluation of groundwater issues and the implementation of management solutions require hydrogeological data that are in part 'baseline' and in part 'time-variant'. The collection of the 'time-variant component' (groundwater level monitoring, groundwater quality monitoring, water well abstraction monitoring (direct or indirect), well groundwater level variations, river flow gauging, meteorological observations and satellite land-use surveys) is what is usually considered 'groundwater

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monitoring'. Groundwater monitoring thus comprises the collection, analysis and storage of a range of data on a regular basis according to specific objectives. The type and volume of data required will vary considerably with the management issue being addressed, but is also inevitably dependent upon available financial resources. At the heart of all groundwater investigation and monitoring are wells, of the two basic types indicated below. They represent keyholes to aquifers, which allow groundwater pressure and quality measurements to be made and thus furnish information from which the health of the aquifer system can be judged. When water wells are drilled, they provide one-off unique in-situ data on the groundwater resource and its variation with depth and data acquired during drilling (borehole logging) and initial test pumping form key baseline reference information on groundwater quantity and quality, in addition to their value for the determination of abstraction well potential. However, data collected from water wells once operational are normally more difficult to interpret, because groundwater levels are affected by the drawdown-recovery cycle and pumped-sample quality reflects the variable mixing of groundwater from a wide range of aquifer depths and residence times. The observation wells are dedicated monitoring stations, sited and designed to detect potential changes in groundwater flow and quality design parameters include selection of depth for the intake screen, frequency of measurement (if not continuous) and selection of quality parameters. To overcome the widespread presence of depth variation in hydraulic head and/or groundwater quality, nested piezometers or well clusters can be used. Piezometer nests are more cost effective than observation well clusters, but should only be used if proper sealing can be achieved to prevent vertical flow between their screens.

As part of the continuing work, one observation well was installed at the research field of IWM Division, BARI, Gazipur. Another one was installed at the research field of the RARS, Rahmatpur, Barishal. At RARS Ishurdi, Pabna, an existing well, recently abandoned for water extraction, have been using for the monitoring of groundwater level fluctuations. Ground water level fluctuation data at 7 days' interval have been measuring since the installation of the observation wells.

## Results

### *Installation of an observation well at IWM Division, Gazipur*

An observation well was installed at the IWM experimental field, Joydebpur, Gazipur-1701 on January 08, 2020. The observation well is located between 23.99°N latitude and 90.41°E longitude. Aerial map of the study area with the location of the observation well is shown in Figure 1.

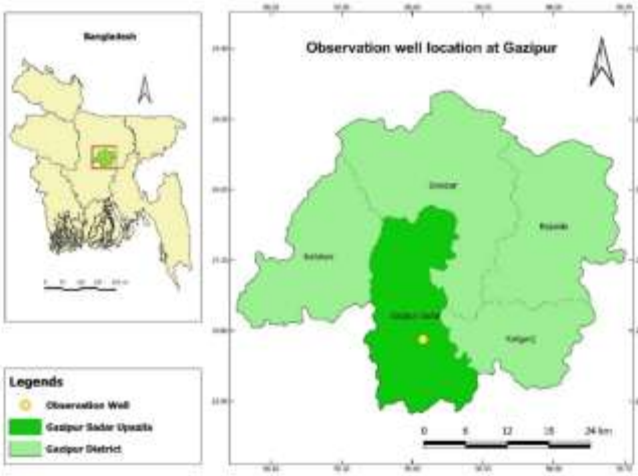


Figure 1. Aerial map and location of the observation well.

The position of the observation well within the IWM research field is presented in Figure 2.


Figure 2. Position of the observation well in the IWM research field.

The installation depth was decided upon careful examination of the water bearing strata during the installation. As such, the depth of boring was 210 ft. including the blind pipe beneath the strainer (5 ft.). The strainer length was 20 ft. A schematic representation of the groundwater observation well is presented in Figure 3.

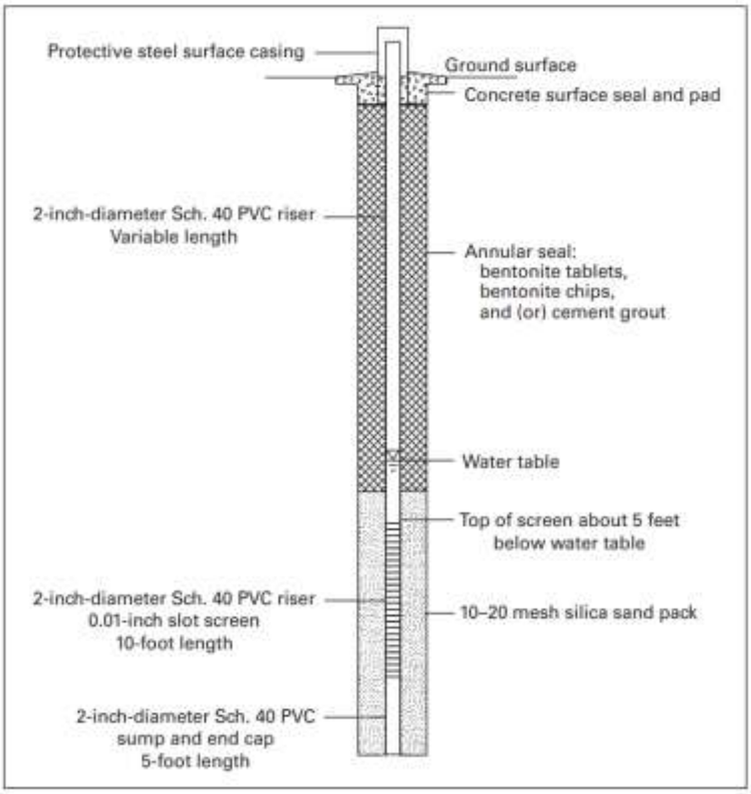


Figure 3. Schematic diagram of groundwater observation well.

After installation, regular monitoring of groundwater level fluctuations at 7 days' interval have been performing. The groundwater level fluctuations at IWM Division, BARI, Gazipur collected during 2019-2020, 2020-2021, and 2021-2022 are presented in Figures 4, 5, and 6, respectively. It is observed from Figures 4 and 5 that GWL reached the lowest (-134 ft) on 12 July 2020 during 2019-2020, whereas, it reached to -137 ft on 18 July 2021 during 2020-2021. It is observed from Figure 6 that the GWL reached its lowest value of -142 ft on 03 July 2022 during the monitoring period 2021-2022.

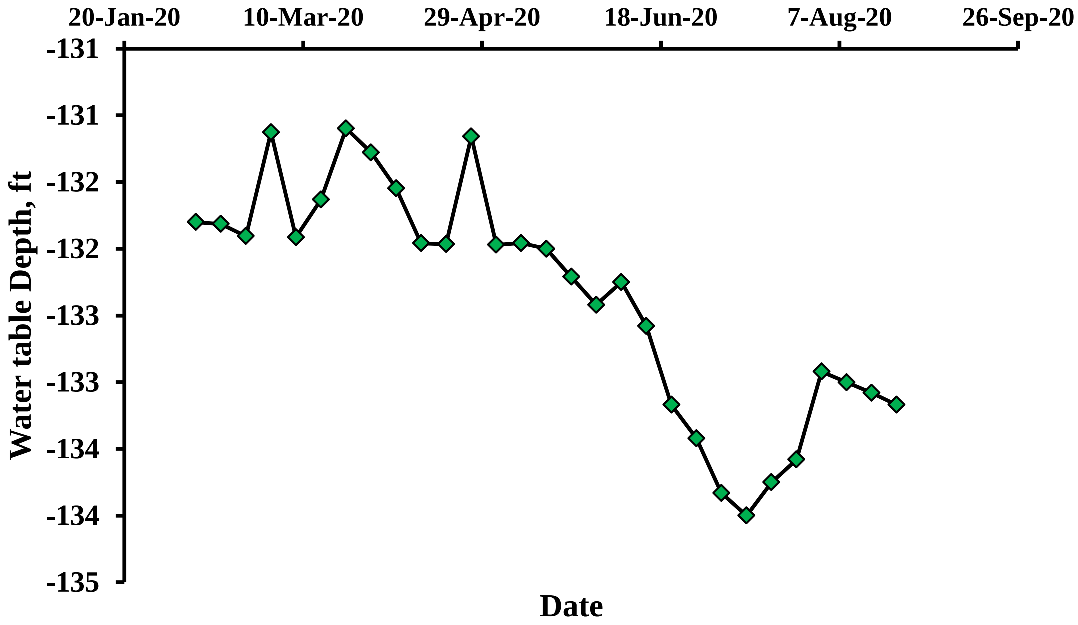


Figure 4. Weekly groundwater level fluctuations during the monitoring period of 2019-2020 at IWM Division, Gazipur.

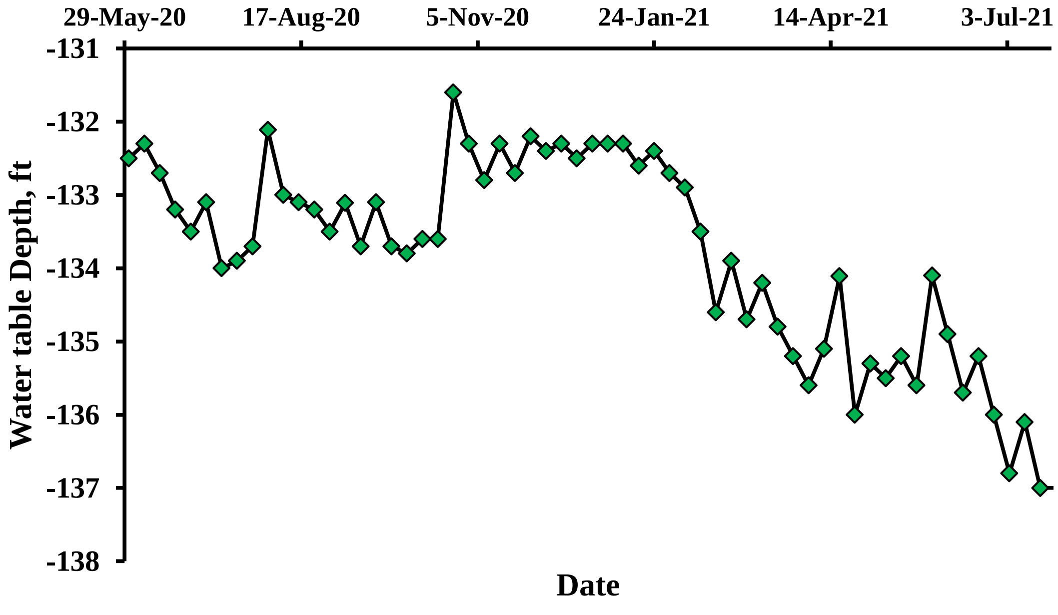


Figure 5. Weekly groundwater level fluctuations during the monitoring period of 2020-2021 at IWM Division, Gazipur.

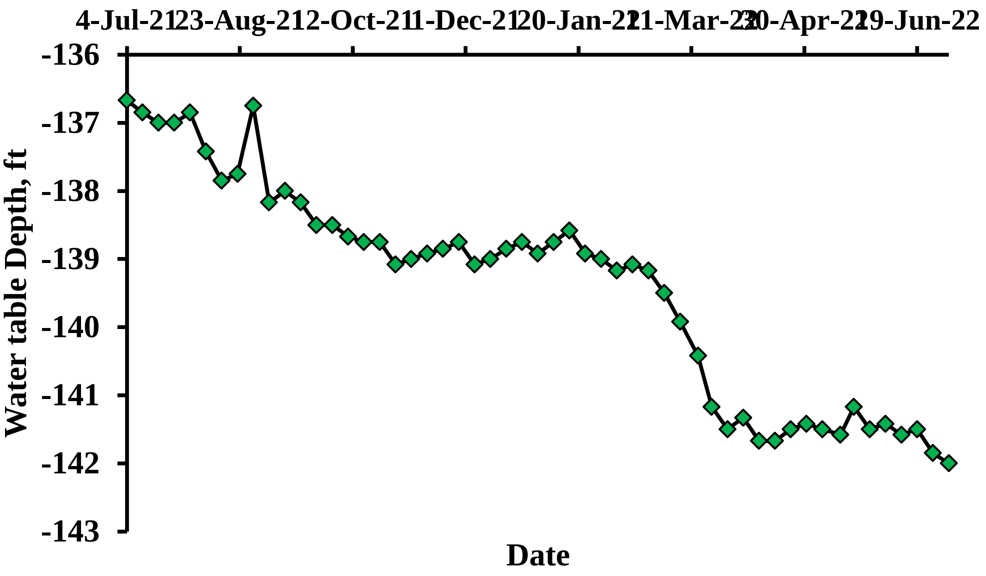


Figure 6. Weekly groundwater level fluctuations during the monitoring period of 2021-2022 at IWM Division, Gazipur.

***Installation of an observation well at RARS, Rahmatpur, Barishal***

Another observation well was installed at the RARS, Rahmatpur, Barishal on February 25, 2020. The observation well is located between 22.79°N latitude and 90.29°E longitude. The installation depth was decided upon careful examination of the water bearing strata during the installation. As such, the depth of boring was 860 ft. including the blind pipe beneath the strainer (5 ft.). The strainer length was 20 ft. The measured water level fluctuations during 2019-2020, 2020-2021, and 2021-2022 are presented in Figures 7, 8, and 9, respectively. It is observed from Figure 6 that during 2019-2020, the lowest level of GWL (-22 ft) was found on 20 June 2020 and on 25 July 2020. On the other hand, Figure 7 reveals that the GWL reached its lowest value (-25.5 ft) on 06 May 2021 during 2020-2021. During the monitoring period 2021-2022, the GWL reached its lowest value (-23.2 ft) on 03 June 2022.

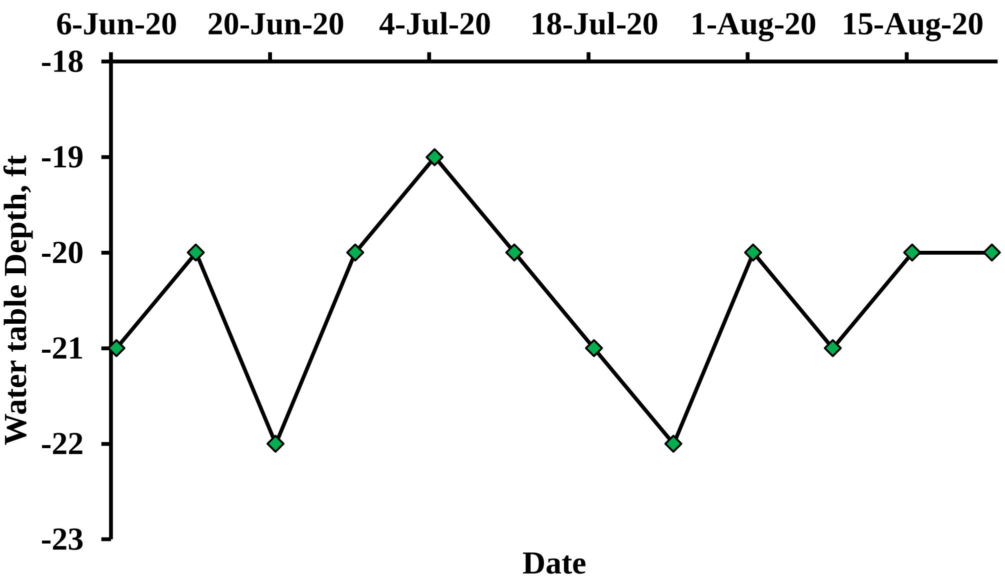

Figure 7. Weekly groundwater level fluctuations during the monitoring period of 2019-2020 at RARS, Rahmatpur, Barishal.

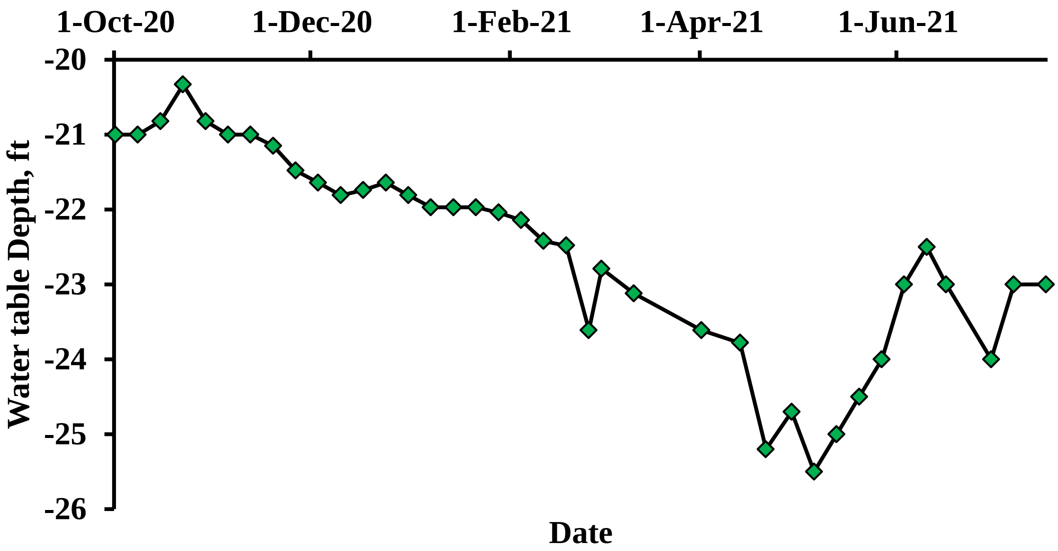


Figure 8. Weekly groundwater level fluctuations during the monitoring period of 2020-2021 at RARS, Rahmatpur, Barishal.

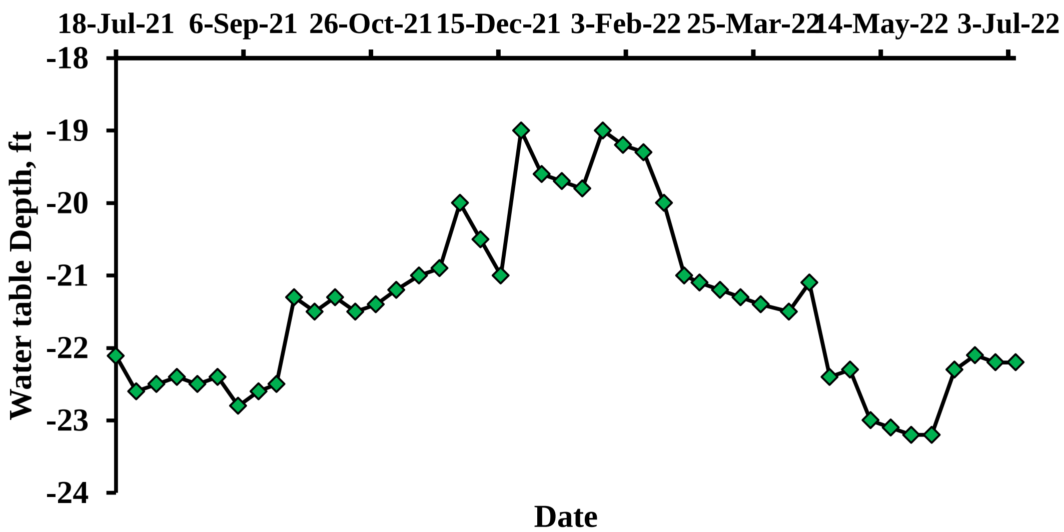


Figure 9. Weekly groundwater level fluctuations during the monitoring period of 2021-2022 at RARS, Rahmatpur, Barishal

***Monitoring of groundwater levels via an existing groundwater well at Ishurdi, Pabna***

The selected observation well is located between 21.12°N latitude and 89.08°E longitude. The depth was 120 ft with a strainer length of 20 ft. The measured water level fluctuations during 2020-2021, and 2021-2022 are presented in Figures 10 and 11, respectively. Figure 10 showed that GWL reached to the lowest level of -29.50m on 21 April 2021 during the monitoring period of 2020-2021 at RARS, Ishurdi. The monitoring of GWL fluctuations during the monitoring period 2021-2022 revealed that the GWL reached to -29.75 on 21 April 2021.

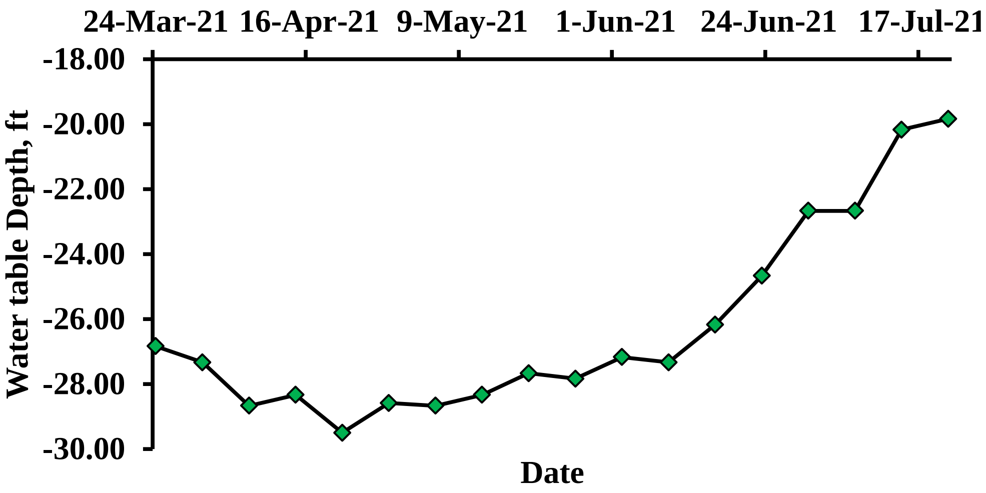


Figure 10. Weekly groundwater level fluctuations during the monitoring period of 2020-2021 at RARS, Ishurdi, Pabna

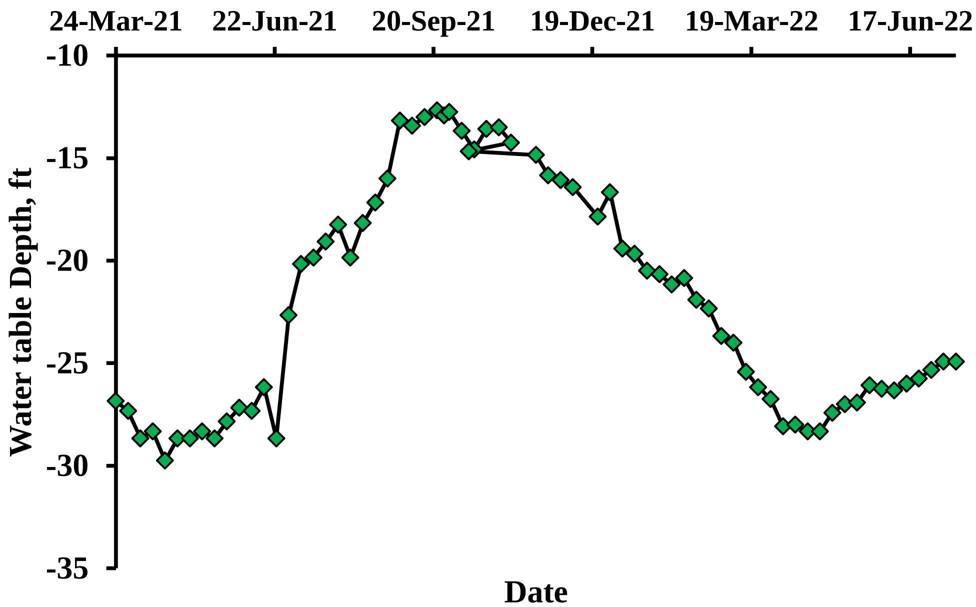


Figure 11. Weekly groundwater level fluctuations during the monitoring period of 2021-2022 at RARS, Ishurdi, Pabna

## Conclusions

Two observation wells, one at IWM Division, BARI, Gazipur while another one at RARS, Rahmatpur, Barishal were installed thus far. At RARS Ishurdi, Pabna, an existing groundwater well was selected for the monitoring purpose. Therefore, the results presented in this report were based on the installed observation wells (Gazipur and Barishal) for the monitoring period of 2019-2020, 2020-2021, and 2021-2022 as well as the selected observation well at Ishurdi during 2020-2021 and 2021-2022. Another two observation well was installed at BSPC, Debigonj at SRC, Bogura. The study should be continued for performing the installation of other observation wells at other BARI stations.

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# ASSESSMENT OF GROUNDWATER QUALITY FOR IRRIGATION AND DRINKING PURPOSES IN SOME SELECTED BARI RESEARCH STATION

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## Abstract

*The present investigation is aimed at understanding the temporal and spatial variability of groundwater quality for its use in irrigation and drinking purposes in different regional station of BARI. The groundwater samples of STWs, DTWs and HTWs that used for irrigation and domestic uses were collected during November – December of 2021 in pre-irrigation season and during March – April of 2022 in post-irrigation season. Water quality indices, namely sodium adsorption ratio (SAR), exchangeable or soluble sodium percent (SSP or %Na), residual sodium carbonate (RSC) and Kelly's ratio (KR) were calculated for separate bore wells. Besides, the composite influence of different water quality parameters on the overall quality of water was also assessed using water quality index (WQI). The upper limit of SAR of 0.41 (less than 10), SSP 17.06% (less than 20%), RSC 2.54, and KR of 0.304 (<1) implies that all the groundwater samples were suitable for irrigation. According to the WQI values, all the samples were found to be "excellent" except few were found "good" in post-irrigation season. Thus, the majority of the area is occupied by good water in both pre- and post-irrigation season.*

## Introduction

Groundwater has become the main source of water use in the agricultural sector in many countries where surface water is not sufficient. Worldwide, irrigation accounts for about 70% of the global fresh water withdrawals and 90% of consumptive water uses (Siebert et al, 2010). In north-west region of Bangladesh, groundwater is a primary source for domestic and irrigation uses. Presently, about 4.2 million ha of land is irrigated by groundwater whereas only 1.03 million ha is irrigated by surface water (BADC, 2013). The contribution of groundwater in irrigation has increased from 41% in 1980/1981 to 78% in 2011/2012 and surface water has declined from 62% to 22% accordingly. Since last couple of decades, groundwater is being extensively used for drinking, irrigation and several other purposes that eventually declining groundwater level in north-west Bangladesh. Declining groundwater levels can lead to poorer water quality as groundwater quality generally degrades with increasing depth within an aquifer. However, degradation of water quality is one of the problems of the 21st century (Oki and Akana, 2016). Globally, anthropogenic activities such as urbanization, industrial development and agricultural intensification are degrading groundwater quality (Li, 2016; Li et al., 2017; Nair et al., 2015). Therefore, poor groundwater quality for irrigation purpose is a matter of worry in recent years. Over chemical fertilization is resulting in groundwater pollution (Ayers and Westcot 1985; Singh et al. 2013; Gautam et al. 2015, Nemčić-Jurec et al. 2017). Groundwater quality also depends on the nature of recharging water, precipitation, subsurface and surface water and hydro-geochemical processes in aquifers (Keesari et al. 2016a; Das et al. 2017), land-use/land-cover change (Amin et al. 2014; Srivastava et al. 2013; Rawat et al. 2017) and mining activities (Keesari et al. 2016b; Gautam et al. 2018). Temporal changes in the constitution and origin of the water recharged, and human factor, frequently cause periodic changes in groundwater quality (Milovanovic 2007).

Groundwater quality degrades in two ways: firstly, due to geochemical reactions in the aquifers and soils and, second, time when it is supplied through improper canals/drainages for irrigation. Therefore, it is necessary to perform a regular assessment of irrigation and drinking water quality (Gupta et al. 2009; Jacintha et al. 2016; Rawat et al. 2018; Gautam et al. 2018). Irrigation demands sufficient water supply of usable quality. The index based on composition and concentration of dissolved elements in water can be useful in determining its applicability for agricultural utilization (Gautam et al. 2013; Singh et al. 2013, 2015). The suitability of groundwater for irrigation depends on the nature of the mineral elements in the water and their impacts on both the soil and plants (Richards 1954; Singh et al. 2009).

Irrigation water quality refers to the kinds and amounts of salts present in the water and their effects on plant growth and development. Generally, water quality parameters such as major cations ($Na^+$, $Ca^{2+}$, $Mg^{2+}$, $K^+$) and anions ($Cl^-$, $SO_4^{2-}$, $HCO_3^-$, $CO_3^{2-}$, $NO_3^-$) and heavy metals are indicators of drinking water use, while water quality indices such as sodium adsorption ratio (SAR), sodium percentage (SSP; %Na), residual sodium carbonate (RSC), residual alkalinity (RA), Kelly's ratio (KR) or Kelly's index (KI), permeability index (PI), chloroalkaline indices (CAI1 and CAI2), potential salinity (PS), magnesium hazard (MH) (or magnesium adsorption ratio; MAR), total dissolved solids (TDS) and total hardness (TH) based on primary water quality parameters are frequently used to determine quality of water for irrigation (Singh et al. 2013, 2015; Gautam et al. 2015). The suitability of water for irrigation is also determined by computing water quality index which is one of the most effective, simple and easily understandable tools to assess water quality for its suitability for various purposes (Singh et al., 2013). To get a comprehensive picture of overall quality of water, the WQI is used. WQI is defined as a rating reflecting the composite influence of different water quality parameters on the overall quality of water.

In the present study, forty groundwater samples collected from STW and DTWs were analyzed and assessed for temporal variation and change in water quality index over a period of time. Most of the bore wells are from agricultural areas. The relation between irrigation and groundwater resources is highly interlinked. The assessment of groundwater quality has become a necessary and important task for the present and future groundwater quality management. Therefore, the aim of the study was to explore the temporal and spatial variability of groundwater quality in the context of its use in irrigation purpose based on computed water quality index values.

## Materials and Methods

In this investigation, groundwater samples of 40 tube wells were collected from STWs and DTWs during November to December 2018 for the pre-irrigation season and during April to May 2019 for the post-irrigation season. Depth of water levels of selected wells were also measured from the ground surface during the pre- and post-irrigation season. A handheld global positioning system (GPS, Model GARMIN GPSMAP 78 s) was used to determine the tube well locations (longitude and latitude). The samples were collected after 10 minutes of pumping and stored in properly washed polyethylene bottles at $4^0$C until the analyses were done. Each of the groundwater samples was analyzed for various physicochemical parameters such as pH; electrical conductivity at $25^0$C; total dissolved solids (TDS); major cations—sodium ($Na^+$), potassium ($K^+$), calcium ($Ca^{2+}$) and magnesium ($Mg^{2+}$); major anions—bicarbonate ($HCO_3^-$), chloride ($Cl^-$), nitrate ($NO_3^-$) and sulphate ($SO_4^{2+}$); components such as iron (Fe), manganese (Mn), arsenic (As) and zinc (Zn). Test methods followed are the standard procedures recommended by American Public Health Association (APHA, 2005). Groundwater suitability for irrigation purpose in this study area was assessed using SAR (Sodium Adsorption Ratio), RSC (Residual Sodium carbonate), SSP (Soluble Sodium percentage) and KR (Kelly's ratio). All determined groundwater concentrations used in assessing these indices were in meq/l.

SAR (Sodium Adsorption Ratio) is a measure of suitability of water for irrigation with respect to the sodium hazard. The SAR values were calculated using equation,

$$SAR = \frac{Na^+}{(\sqrt{Ca^{+2} + Mg^{+2}})/2}$$

The residual sodium carbonate is a measure of the hazard involved in the use of high carbonate waters. RSC is calculated as follows:

$$RSC = (CO_3^{2-} + HCO_3^{-}) - (Ca^{+2} + Mg^{+2})$$

Kelly (1940) and Paliwal (1967) introduced another factor to assess quality and classification of water for irrigation purpose based on the concentration of $Na^{+}$ against $Ca^{2+}$ and $Mg^{2+}$. It can be calculated using the following equation:

$$KR = \frac{Na+}{Ca2+ + Mg\,2+}$$

KR > 1 indicates an excess level of $Na^{+}$ in waters. Therefore, water with a KI ≤ 1 has been recommended for irrigation, while water with KI ≥ 1 is not recommended for irrigation due to alkali hazards (Ramesh and Elango 2012; Karanth 1987).

To get a comprehensive picture of overall quality of groundwater, the WQI was used. WQI is defined as a rating reflecting the composite influence of different water quality parameters on the overall quality of water. The FAO standard specified for irrigation water was used for the calculation of WQI. The WQI was computed through three steps. First, each of the measured parameters (pH, EC, TDS, Na, Ca, Mg, K, $CO_3$, $HCO_3$, Cl, $SO_4$, $NO_3$, $PO_4$, Fe, Zn and B) was assigned a weight ($w_i$) according to its relative importance in the overall quality of water for irrigation purposes. The maximum weight 5 was assigned to parameters like pH, EC, TDS, $Na^{+}$, $Cl^{-}$ , and $SO_4^{2-}$ due to their importance in water quality assessments. A minimum weight 1 was assigned to zinc because of its insignificant role. Other parameters were assigned weights between 1 and 5 based on their relative importance in the evaluation of water quality (Table 1).

Table 1. Relative weight of chemical parameters

| Parameter | FAO standard | Weight (wi) | Relative weight (Wi) |
|---|---|---|---|
| pH | 6.5-8.4 | 5 | 0.0862 |
| EC (mS/cm) | 2250 | 5 | 0.0862 |
| TDS (mg/L) | 500 | 5 | 0.0862 |
| Ca (mg/L) | 200 | 4 | 0.0690 |
| Mg (mg/L) | 100 | 4 | 0.0690 |
| Na (mg/L) | 200 | 5 | 0.0862 |
| K (mg/L) | 10 | 3 | 0.0517 |
| Cl (mg/L) | 350 | 5 | 0.0862 |
| HCO3 (mg/L) | 400 | 3 | 0.0517 |
| NO3 (mg/L) | 50 | 3 | 0.0517 |
| PO4 (mg/L) | 10 | 3 | 0.0517 |
| SO4 (mg/L) | 250 | 5 | 0.0862 |
| Fe (mg/L) | 3 | 5 | 0.0862 |
| Zn (mg/L) | 5 | 1 | 0.0172 |
| B (mg/L) | 3 | 2 | 0.0345 |

In the second step, the relative weight (Wi) of the chemical parameter was computed using the following equation:

$$Wi = wi / \sum_{i=1}^{n} \mathrm{wi}$$

Where $W_i$ is the relative weight, $w_i$ is the weight of each parameter, and n is the number of parameters.

In the third step, a quality rating scale ($q_i$) for each parameter is assigned by dividing its concentration in each water sample by its respective standard according to the guidelines given by FAO, 1997 and the result is multiplied by 100:

$$qi = (Ci/Si) \times 100$$

Where $q_i$ is the quality rating, $C_i$ is the concentration of each chemical parameter in each water sample in mg/L, and $S_i$ is the irrigation water standard for each chemical parameter in mg/L.

For computing WQI, the sub index (SI) is first determined for each chemical parameter, as given below:

$$SI = Wi \times qi$$

$$WQI = \sum SIi\text{-}n$$

Where $SI_i$ is the sub index of $i^{th}$ parameter; $W_i$ is relative weight of $i^{th}$ parameter; $q_i$ is the rating based on concentration of $i^{th}$ parameter, and n is the number of chemical parameters. The computed WQI values are classified into five categories: excellent water (WQI < 50); good water (WQI = 50–100); poor water (WQI = 100–200); very poor water (WQI = 200–300); and water unsuitable for irrigation (WQI > 300).

## Results and Discussion

### Suitability of groundwater for irrigation

The chemical compositions of the collected groundwater samples in pre-irrigation and post-irrigation season are presented in Table 2a and 2b, respectively. The pH value were found slightly higher in post-irrigation season than pre-irrigation season. The pH values of groundwater samples in the study area ranged from 7.10 to 7.37, and 7.14–7.44 for pre- and post-season irrigation periods respectively. The high pH value indicated the slight alkalinity of water, possibly due to the presence of appreciable amounts of sodium, calcium, magnesium, and carbonate ions (Rao *et al*., 1982). All the samples conform to FAO standard of 6.5 – 8.4 for irrigation use. The range of electrical conductivity (EC) was 0.355 – 0.425 dS/m in pre-irrigation season and 0.362 – 0.468 dS/m in post-irrigation season. Over the seasons, EC value of groundwater of the study area ranged from 0.35 to 0.46 dS/m with an average value range 0.38 – 0.42 dS/m, which according to Wilcox (1955) falls within the irrigation water quality classification stand ‘excellent to good’. In terms of the ‘degree of restriction on use’, EC value of < 700 µS/cm refers the water to ‘none’; 700-3000 µS/cm ‘slight to moderate’ and 3000 µS/cm ‘severe’ (UCCC, 1974). It is easily presumable from the EC values in Table 2a and 2b, all water samples of the study area is suitable for irrigation purpose as it falls under category ‘none’ (UCCC, 1974).

The concentrations of $Na^+$, $Ca^{++}$, $Mg^{++}$, and $K^+$ in water samples varied in the ranges of 5.04-8.72, 25.6-42.21, 0.95-3.58 and 1.05-1.72 mg/L in pre-irrigation season and in the ranges of 5.16-9.32, 22.8-44.21, 1.05-4.38 and 0.772-1.77 mg/L respectively in post-irrigation season. Recommended maximum concentrations of $Na^+$, $Ca^{++}$, $Mg^+$ and $K^+$ for long-term irrigation use on all soils are 200, 200, 100 and 10 mg/L, respectively (Ayers and Westcot, 1985). Therefore, all the samples in the study area can be used safely for long-term irrigation.

One of the toxic major ions in irrigation water is chloride (Bouderbala 2015). Chlorides are not absorbed or held back by soils, therefore, it moves readily with the soil-water, and is taken up by the crops, moves

**Table 2a. Mean quality parameters of groundwater at different study sites during November - December 2018**

| Location | Source | pH | EC (dS/m) | Na | Ca | Mg | K | HCO3 | NO3 | PO4 | SO4 | Cl- |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Bogura | DTW | 7.22 | 0.355 | 5.16 | 25.6 | 1.10 | 1.72 | 207.12 | 0.58 | 0.118 | 6.74 | 1.57 |
| | STW | 7.10 | 0.410 | 5.06 | 35.2 | 1.18 | 1.53 | 199.27 | 0.63 | 0.241 | 7.24 | 1.38 |
| | HTW | 7.32 | 0.430 | 5.33 | 32.4 | 1.42 | 1.52 | 225.68 | 0.60 | 0.243 | 8.12 | 1.47 |
| Ishurdi | DTW-1 | 7.37 | 0.340 | 5.42 | 26.8 | 0.95 | 1.05 | 207.80 | 0.66 | 0.116 | 6.96 | 1.49 |
| | DTW-2 | 7.26 | 0.375 | 5.94 | 37.2 | 1.05 | 1.05 | 207.80 | 0.62 | 0.118 | 7.62 | 1.53 |
| | HTW | 7.53 | 0.380 | 5.50 | 28.4 | 1.12 | 1.17 | 244.48 | 0.74 | 0.116 | 8.07 | 1.67 |
| Rajshahi | DTW | 7.13 | 0.370 | 8.72 | 36.4 | 1.55 | 1.72 | 266.70 | 0.83 | 0.118 | 7.73 | 1.44 |
| | STW | 7.15 | 0.365 | 8.16 | 34.24 | 1.45 | 1.53 | 278.90 | 0.78 | 0.116 | 9.63 | 1.52 |
| Jashore | DTW | 7.28 | 0.425 | 6.59 | 42.21 | 3.58 | 1.52 | 295.26 | 0.77 | 0.116 | 6.30 | 1.56 |
| | STW | 7.12 | 0.350 | 5.04 | 24.3 | 1.22 | 1.05 | 203.06 | 0.68 | 0.120 | 5.63 | 1.32 |
| Range | | 7.10-7.37 | 0.355-0.425 | 5.04-8.72 | 25.6-42.21 | 0.95-3.58 | 1.05-1.72 | 207.12-295.26 | 0.58-0.83 | 0.118-0.243 | 5.63-9.63 | 1.44-1.67 |
| Average | | 7.258 | 380 | 6.09 | 32.28 | 1.46 | 0.672 | 253.61 | 0.689 | 0.14 | 7.40 | 1.50 |

in the transpiration stream and accumulates in the leaves. If the chloride concentration in the leaves exceeds the tolerance of the crop, injury symptoms develop, such as leaf burn or drying of the leaf tissue, yellowing of leaf and spotting on the leaf. High content of Cl- in water also limits its use in sprinkler irrigation. In the present study, chloride concentration varied from 1.44-1.67 in pre-irrigation season and 1.46-1.85 mg/L in post-irrigation irrigation, respectively which fall under excellent category according Ayre and Westcot (1985). The upper limit of $NO_3^-$ , $SO_4^{--}$, $PO^{4-}$ and $HCO_3^-$ was 0.73, 10.06, 0.248 and 384.20 mg/L respectively which is far below their corresponding recommended levels of 50, 250, 10 and 400 mg/L. So, these parameters might not be problematic for irrigation use.

**Table 2b. Mean quality parameters of groundwater at different study sites during March – April 2019**

| Location | Source | Parameters, mg/L except pH | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | pH | EC (dS/m) | Na | Ca | Mg | K | HCO3 | NO3 | PO4 | SO4 | Cl- |
| Bogura | DTW | 7.41 | 0.382 | 5.42 | 25.8 | 1.18 | 1.77 | 214.32 | 0.63 | 0.122 | 6.82 | 1.71 |
| | STW | 7.14 | 0.420 | 5.16 | 34.8 | 1.24 | 1.62 | 219.28 | 0.67 | 0.248 | 7.28 | 1.57 |
| | HTW | 7.72 | 0.446 | 5.63 | 35.6 | 1.48 | 1.56 | 234.78 | 0.64 | 0.248 | 7.66 | 1.62 |
| Ishurdi | DTW-1 | 7.44 | 0.362 | 5.50 | 22.8 | 1.05 | 1.15 | 212.8 | 0.72 | 0.202 | 6.94 | 1.72 |
| | DTW-2 | 7.26 | 0.365 | 6.04 | 23.6 | 1.12 | 1.18 | 216.6 | 0.70 | 0.204 | 7.54 | 1.81 |
| | HTW | 7.23 | 0.410 | 5.70 | 28.4 | 1.16 | 1.18 | 253.68 | 0.78 | 0.118 | 8.19 | 1.85 |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Rajshahi | DTW | 7.16 | 0.384 | 9.32 | 37.2 | 1.42 | 0.772 | 276.8 | 0.84 | 0.202 | 7.78 | 1.66 |
| | STW | 7.25 | 0.374 | 8.99 | 35.32 | 1.40 | 0.694 | 284.2 | 0.88 | 0.118 | 10.06 | 1.58 |
| Jashore | DTW | 7.38 | 0.468 | 6.76 | 44.21 | 4.38 | 1.18 | 306.06 | 0.79 | 0.118 | 6.32 | 1.76 |
| | STW | 7.22 | 0.368 | 5.38 | 26.62 | 1.72 | 0.947 | 182.26 | 0.71 | 0.124 | 5.66 | 1.46 |
| Range | | 7.14-7.44 | 0.362-0.468 | 5.16-9.32 | 22.8-44.21 | 1.05-4.38 | 0.772-1.77 | 212.8-306.06 | 0.63-0.88 | 0.118-0.248 | 5.66-10.06 | 1.46-1.85 |
| Average | | 7.36 | 396.90 | 6.39 | 31.44 | 1.62 | 1.21 | 260.08 | 0.736 | 0.17 | 31.44 | 1.67 |

The suitability of groundwater for irrigation is dependent on the effects of the mineral constituents of the water on both the plant and the soil. In this study, SAR, SSP, RSC and KR were used to carry out the assessment of the suitability of water for irrigation purposes (Table 3). Irrigation water that has high sodium ($Na^{+}$) content can bring about a displacement of exchangeable cations $Ca^{2+}$ and $Mg^{2+}$ from the clay minerals of the soil, followed by the replacement of the cations by sodium. SAR (Sodium Adsorption Ratio) is a measure of suitability of water for irrigation with respect to the sodium hazard. As higher deposition of sodium may cause damage to soil, soil irrigation with high sodium depositing waters are not suitable. SAR is directly related to adsorption of sodium by soil, therefore it is a better measure of sodium (alkali) hazard in irrigation water. High SAR in any irrigation water implies hazard of sodium (Alkali) replacing Ca and Mg of the soil through cation exchange process, a situation eventually damaging to soil structure, namely permeability which ultimately affects the fertility status of the soil and reduce crop yield (Gupta, 2005). SAR gives the clear idea about the adsorption of sodium by soil. Based on the grading criteria of water for irrigation, SAR is classified into excellent (<10), good (10-18), permissible (18-26), unsuitable (>26) (Khodapanah et al. 2009). The assessment results with these methods are listed in Table 53b. As per SAR value all samples collected either from STW or from DTW in both seasons fall into excellent category. During pre-irrigation season the values of SAR of the collected water samples ranged from 0.40 to 0.99 with an average value of 0.62 and it ranged from 0.69 to 0.95 during post-irrigation season with an average value of 0.79.

The residual sodium carbonate (RSC) is a measure of the hazard involved in the use of high carbonate waters. Water quality for irrigation is influenced when concentration of carbonates and bicarbonates is higher than calcium and Magnesium. Waters containing high concentrations of these ions, calcium and possibly magnesium ($Mg^{+2}$) may precipitate as carbonates when water is concentrated by transpiration and evaporation. With the removal of calcium and magnesium from soil solution, the relative proportion of sodium is increased with attendant increase in alkali hazard. A high range of RSC in irrigation water means an increase in the adsorption of sodium on the soil. Water having RSC > 5 has not been recommended for irrigation because of damaging effects on plant growth. According to USDA (United State Department of Agriculture) any source of water in which RSC is higher than 2.5 is not considered suitable for agriculture purpose, and water < 1.25 is recommended as safe for irrigation purpose. A negative value of RSC reveals that concentration of $Ca^{2+}$ and $Mg^{2+}$ is in excess. A positive RSC denotes that $Na^{+}$ existences in the soil are possible. RSC calculation is also important in context to calculate the required amount of gypsum or sulfuric acid per acre-foot in irrigation water to neutralize residual carbonates effect. RSC values for pre-irrigation season varied from 1.47 to 2.74 with an average value of 2.09 while for post-irrigation season SRC values varied from 1.51 to 2.78 with an average value of 2.23. The RSC value was found somewhat higher (>2.50) in one DTW of Jashore. In both the seasons, however, KR values were found less than 1, indicating that all groundwater samples are suitable for irrigation use.

**Table 3. Water quality indices for suitability assessment of different water sources for irrigation**

| Location | Source | Pre-irrigation | | | | Post-irrigation | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | SAR | RSC | SSP | KR | SAR | RSC | SSP | KR |
| Bogura | DTW | 0.27 | 2.02 | 13.68 | 0.164 | 0.28 | 2.13 | 14.13 | 0.170 |
| | STW | 0.23 | 1.41 | 10.39 | 0.118 | 0.23 | 1.75 | 10.65 | 0.122 |
| | HTW | 0.25 | 1.96 | 11.54 | 0.133 | 0.25 | 1.95 | 11.20 | 0.129 |
| Ishurdi | DTW-1 | 0.28 | 1.99 | 14.02 | 0.166 | 0.31 | 2.26 | 15.98 | 0.195 |
| | DTW-2 | 0.26 | 1.46 | 11.57 | 0.133 | 0.33 | 2.28 | 16.77 | 0.206 |
| | HTW | 0.27 | 2.49 | 13.41 | 0.158 | 0.28 | 2.64 | 13.81 | 0.163 |
| Rajshahi | DTW | 0.38 | 2.42 | 16.15 | 0.195 | 0.41 | 2.56 | 16.86 | 0.205 |
| | STW | 0.37 | 2.74 | 16.09 | 0.194 | 0.40 | 2.78 | 17.06 | 0.208 |
| Jashore | DTW | 0.26 | 2.43 | 10.53 | 0.119 | 0.26 | 2.44 | 10.14 | 0.114 |
| | STW | 0.27 | 2.01 | 14.06 | 0.166 | 0.27 | 1.51 | 13.50 | 0.159 |
| Range | | 0.23-0.38 | 1.41-2.74 | 11.77-15.20 | 0.139-0.230 | 1.22-1.48 | 1.51-2.78 | 10.14-17.06 | 0.114-0.208 |
| Average | | 0.28 | 2.09 | 13.14 | 0.15 | 0.30 | 2.23 | 14.01 | 0.17 |

Soluble Sodium Percent (SSP) is also used to evaluate sodium hazard. Water with a SSP greater than 60% may result in sodium accumulations that will cause a breakdown in the soil's physical properties (Khodapanah et al. 2009). The values for the soluble sodium percent (SSP) in the study areas were found to vary from 11.77-15.20% with an average value of 13.14 % in pre-irrigation season and from 10.14-17.06% with an average value of 14.01 in post-irrigation season (Table 2b). This result corroborates the findinds of Khan *et al*. (1989) who found SSP ranging from 14.50 to 37.55 in the North-West region of Bangladesh. Based on the classification after Wilcox (1955) for SSP, all samples fall under excellent and good class, so can be used safely for irrigation.

In the study area, the assessment of groundwater quality for irrigation was also carried out through the estimation of Water Quality Index (WQI) to identify its suitability for irrigation purpose (Fig. 1). This index is an important parameter for assessing groundwater quality and its suitability (Avvannavar and Shrihari, 2008). The advantage of water quality index is based on the relative importance of essential parameters with respect to standards of irrigation purposes.

The WQI ranged from 37.17 to 49.11 for DTW and from 36.0 to 49.96 for STW in pre-irrigation season while it ranged from 38.03 to 50.19 and 36.32 to 50.80, respectively for DTW and STW in post-irrigation season. While for HTW, it ranged from 41.22 to 44.75 with higher value in the post-irrigation season. According to the WQI values, all the samples were found to be "excellent" in pre-irrigation season whereas in post-irrigation season, all samples were found also "excellent" except samples of Rajshahi in which WQI goes slightly beyond the "excellent" category. Dissolved ions such as Na, K, Mg, $HCO_3$, Cl, $NO_3$, and $SO_4$, during post-monsoon period affected WQI values. High iron concentration in groundwater caused high WQI values; high chloride concentrations also contributed to high WQI values typically during the post-monsoon period. In general, the values of all quality indices were lower in pre-irrigation season than post-irrigation season indicate that water quality of groundwater was better when aquifer is almost fully recharged and depth of water table is minimum. This may be due to dilution effect that happened through rainwater (Srivastava, 2019).

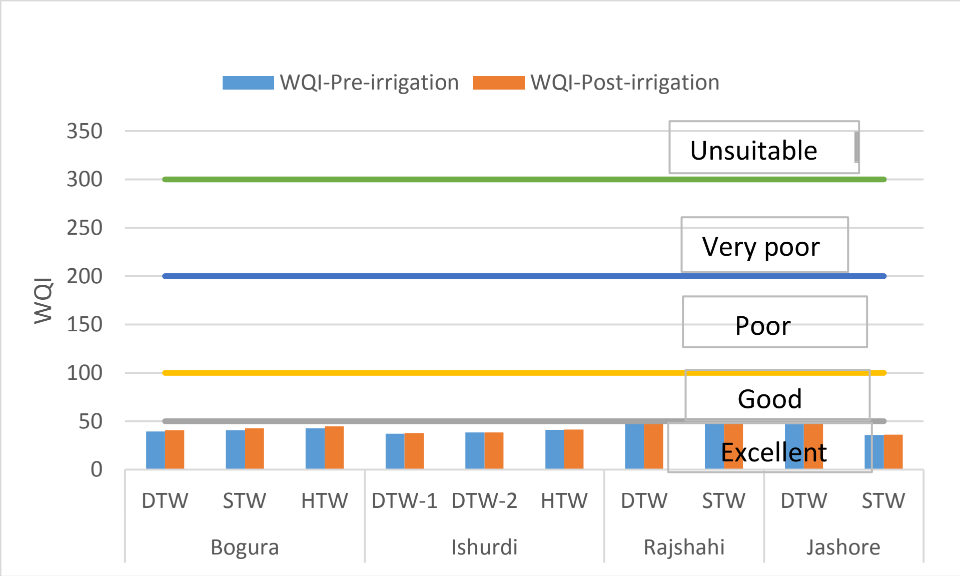


Fig.1. Water quality index (WQI) of groundwater at different location of the study area (solid line represents the range of different categories of water quality)

Groundwater of the study areas were classified into different categories by using different quality indices such as SAR, SRC, SSP, KR and WQI (Table 3). As per SAR values, all samples collected from DTWs, STWs and HTWs were fall in excellent category both in pre-irrigation and post-irrigation seasons as SAR values determined as <10. As per RSC values of all samples except one STW of Rajshahi fall into permissible category in both pre- and post-irrigation seasons. One sample from HTW of Ishurdi and another from DTW of Bogura were found permissible for irrigation as SRC value was greater than 2.5. But all other samples of DTWs, STWs and HTWs were found suitable for irrigation purpose in both pre- and post-irrigation season. In respect of sodium hazards (SSP), all water samples were fall under excellent category. Irrespective of DTW, STW or HTW, KR values of all groundwater samples were less than 1.0 indicate low Na+ ion in water; hence it was suitable for irrigation (Ehya and Saeedi, 2018). The estimation of water quality index (WQI) of all samples collected in pre- and post-irrigation seasons showed that almost all HTWs, STWs and DTWs water was excellent, except water samples of Rajshahi which was found good for irrigation.

**Table 3: Classification of groundwater quality in the study area**

| Quality index | Categories | Ranges | Sources of water | |
|---|---|---|---|---|
| | | | Pre-irrigation | Post-irrigation |
| SAR | Excellent<br>Good<br>Permissible<br>Unsuitable | <10<br>10 – 18<br>18 – 26<br>>26 | STW, DTW, HTW | STW, DTW, HTW |
| RSC | Excellent<br>Permissible<br>Unsuitable | <1.25<br>1.25-2.5<br>>2.5 | STW, DTW, HTW<br>- | -<br>STW(Rajshahi), DTW (Bogura)<br>- |

| | | | | |
|---|---|---|---|---|
| SSP | Excellent | 0 – 20 | STW, DTW, HTW | STW, DTW, HTW |
| | Good | | | - |
| | Permissible | 20 – 40 | | - |
| | Doubtful | 40 – 60 | | - |
| | Unsuitable | 60 – 80 | | - |
| | | >80 | | |
| KR | Suitable | <1 | STW, DTW, HTW | STW, DTW, HTW |
| | Unsuitable | ≥ 1 | | |
| WQI | Excellent | <50 | STW, DTW, HTW | - |
| | Good | 50 – 100 | - | STW, DTW( Rajsahi) |
| | Poor | 100 – 200 | - | - |
| | Very poor | 200 – 300 | - | - |
| | Unsuitable | >300 | | |

## Suitability of groundwater for drinking

Quality parameters of groundwater were evaluated for drinking purposes by comparing the parameter value with the respective parameters recommended by the WHO (1997). It is clear from Table 4 that pH, EC, $Na^+$, $Ca^{2+}$, $Mg^{2+}$, $Cl^-$, $HCO_3^{\ -}$, $NO_3^-$, $SO_4^{2+}$ and $Cl^-$ values were far below the standard limit for drinking water set by the WHO (1997) and Department of Environment (DoE 1989). Only three of the groundwater samples show high TDS concentrations. None of the samples were exceed the allowable limit for drinking purposes (WHO, 1997; DoE, 1989).

**Table 4: Comparision of the groundwater samples of the study area with the standard limit prescribed by WHO (1997) and EQS (1989) for drinking water purposes**

| Parameter | WHO standard (1997) | Bangladesh standard (DoE, 1989) | Range | Average | Median | Std. dev | No. of samples above acceptable limit |
|---|---|---|---|---|---|---|---|
| pH | 6.5-8.5 | 6.5-8.5 | 7.14-7.44 | 7.34 | 7.36 | 0.37 | None |
| EC | 400 | - | 0.362-0.468 | 383.0 | 396.9 | 37.94 | 3 samples |
| TDS | 500-1000 | 500-1500 | 218-294 | 255.0 | 257.0 | 23.40 | None |
| Na | 200 | 200 | 5.16-9.32 | 5.67 | 6.39 | 1.52 | None |
| K | 12 | 12 | 0.772-1.77 | 1.18 | 1.21 | 0.36 | None |
| Ca | 75-200 | 75-200 | 22.8-44.21 | 31.60 | 31.44 | 6.99 | None |
| Mg | 50-150 | 30-50 | 1.05-4.38 | 1.32 | 1.62 | 0.99 | None |
| Cl | 250 | 150-600 | 1.46-1.85 | 1.69 | 1.67 | 0.12 | None |
| $SO_4$ | 250 | 400 | 5.66-10.06 | 7.41 | 7.43 | 1.19 | None |
| $NO_3$ | 50 | 10 | 0.63-0.88 | 0.74 | 0.72 | 0.08 | None |
| $HCO_3$ | 125-350 | - | 212.8-306.06 | 227.0 | 260.1 | 71.31 | None |
| Fe | 0.3 | 0.3-1.0 | 0.002-0.022 | 0.16 | 0.68 | 0.81 | None |
| Zn | 0.01-3.0 | 1.0 | 0.002-0.022 | 0.011 | 0.010 | 0.010 | None |

The coefficient correlation matrix (r) is one of the important tests that shows the connections between two independent parameters of the water. The most familiar measure of dependence between two parameters of water is the Pearson product moment correlation coefficient matrix (Table 5). It is a measure to demonstrate how well one variable predicts the other (Bahar and Reza 2010; Howlader et al.

| | pH | EC | TDS | Ca | Mg | Na | K | HCO3 | NO3 | PO4 | SO4 | Fe | Zn | B |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| pH | 1.000 | -0.027 | -0.121 | -0.236 | -0.075 | -0.314 | 0.133 | -0.259 | 0.168 | -0.182 | 0.082 | -0.213 | -0.437 | -0.184 |
| EC | | 1.000 | 0.834 | 0.649 | 0.565 | -0.572 | 0.314 | 0.030 | 0.27 | 0.665 | 0.599 | 0.610 | -0.164 | -0.351 |
| TDS | | | 1.000 | 0.544 | 0.422 | -0.516 | 0.689 | -0.108 | 0.076 | 0.703 | 0.691 | 0.896 | -0.237 | -0.364 |
| Ca | | | | 1.000 | 0.670 | 0.525 | -0.561 | 0.480 | 0.389 | 0.128 | 0.238 | 0.208 | 0.338 | 0.128 |
| Mg | | | | | 1.000 | 0.303 | - | 0.393 | 0.128 | - | - | 0.299 | 0.141 | -0.331 |

**Table 5: Correlation coefficient matrix of groundwater quality parameters**

2014). The correlation coefficient, r, ranges from − 1 to + 1. When the value of r is close to − 1, the relationship is demarcated as anti-correlated or has a negative slope. The association is considered to be correlated or have a positive slope, while the value of r is close to + 1. If the value of r tends to be zero, the points are considered to become less correlated and eventually are uncorrelated (Srivastava and Ramanathan 2008; Howlader et al. 2014). The correlation matrices for quality parameters of the groundwater were calculated and shown in Table 5. From Table 5, it can be concluded that EC shows positive correlation only with almost all quality parameters like $Na^+$, $K^+$, $Ca^+$, $Mg^{2+}$, Fe, $PO_4^-$. Moreover, Ca-Mg, Na–K, Na–Ca show the remarkable positive correlation pairs in the analysis. The $SO_4^{2-}$ show positive correlations with the cations like $Na^+$, $HCO^{3-}$ and $NO^{3-}$.

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 0.345 | | | 0.118 | 0.227 | | | |
| Na | 1.000 | -0.700 | 0.962 | 0.630 | -0.361 | 0.519 | -0.426 | 0.159 | 0.281 |
| K | | 1.000 | -0.666 | -0.173 | 0.590 | -0.176 | 0.756 | -0.258 | -0.490 |
| HCO3 | | | 1.000 | 0.659 | -0.321 | 0.556 | -0.336 | 0.238 | 0.702 |
| NO3 | | | | 1.000 | -0.215 | 0.776 | -0.159 | 0.150 | 0.635 |
| PO4 | | | | | 1.000 | 0.120 | 0.742 | -0.283 | -0.199 |
| SO4 | | | | | | 1.000 | -0.222 | 0.428 | 0.744 |
| Fe | | | | | | | 1.000 | -0.409 | -0.552 |
| Zn | | | | | | | | 1.000 | 0.837 |
| B | | | | | | | | | 1.000 |

**Conclusions**

The groundwater quality of some on-station tubewells were evaluated for agricultural and drinking uses. The water quality indices such as SAR, SSP, RSC and KR were calculated to find out its suitability for irrigation. The results based on these indices indicate that quality of groundwater samples fall into excellent and good categories for irrigation use. The water quality index (WQI) has been determined to better assess suitability of groundwater for irrigation and it is observed that all the samples were “excellent” except few were found “permissible” and “good” in post-irrigation season. Comparing with WHO (1997) and DoE (1989) guidelines, all groundwater samples were found suitable for drinking and domestic uses. Therefore, in respect of all evaluating criteria, groundwater of the study area was found suitable and can safely be used for both irrigation and purpose.

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# PROJECT: CONSERVATION OF GROUNDWATER AND RAISING ITS USE EFFICIENCY AND PRODUCTIVITY IN IRRIGATED AGRICULTURE IN BANGLADESH

S.K. BISWAS, G.W. SARKAR, M. ASSADUZZAMAN

## 1. Background

Increased crop production and sustainable agricultural development of Bangladesh is largely depending on judicious use of water which translates into conservation (both groundwater and surface water) wherever possible leading to water savings for either other economic and social uses as well as making it cost effective. Most of the groundwater based irrigation use deep tube well (DTW) and shallow tube well (STW) and surface water based irrigation through low lift pump (LLP). These irrigation devices are mostly operated and managed by the private sector. In case of DTWs, two public organisations, namely BMDA and BADC are active. In case of surface water irrigation BWDB is the main public agency involved.

As of June 2020, the country provided irrigation facilities for about 5.6 Mha, which is about 65% of the total cultivated area of 8.6 Mha. But potential capacity of irrigation facilities developed and conjunctive use of water can irrigate about 76% of the total cultivable area (MoA, 2020), which indicates low efficiency of irrigation system and thus lead to higher irrigation charges than is absolutely essential. Therefore, emphasis should be given on irrigation development with water savings and cost-effectiveness. The Agricultural Policy (2018) has given emphasis on reducing irrigation cost, introduction of efficient irrigation systems and expansion of water saving irrigation facilities with efficient water delivery system from the source to field.

The Government of Bangladesh, after consulting with relevant stakeholders within the government, private sector and civil society, and supported by the 2030 Water Resources Group, World Bank, established the Bangladesh Water Multi-Stakeholder Partnership (BWMSP) with the objective of contributing to addressing challenges in the Water Sector. A study has been carried out on Economic Policy Incentives (EPI) for water resources management. Among others, the EPI study made the recommendation for a transition from a low-productivity, low-efficient and wasteful use of irrigation water to one with higher productivity, higher efficiency and less wasteful system. The report highlighted the following recommendations:

i) A water charge regime based on *volume of water abstracted* rather than on area irrigated for a fixed fee;
ii) A system where individual farmers have direct control over abstraction for irrigating his/her land through *issuance and use of individual smart cards*;
iii) Introduction of *crop water-saving technology* (such as Alternate wetting and drying (AWD)) to minimize need for irrigation water;
iv) Higher *supply-side efficiency* through investment in more efficient water delivery system from the source of water to the field of farmers; and
v) S*ocial mobilization* for a community-based system of water management where the above four types of actions may be combined for wider acceptance by farmers.

These five elements exist in various degrees and form in case of BMDA and BADC deep tube well (DTW) areas. The present study has been carried out to examine how far their combinations support the hypothesis of a change from a low productivity, low efficiency and wasteful water use to a better one. Thus, a socio-economic, institutional and technical survey has been conducted to understand the effectiveness of the five elements of a proposed necessary interventions as indicated in preceding sub-section for ground water conservation, raising water use efficiency and water productivity in BADC and BMDA deep tube well (DTW) areas particularly for dry period boro rice production. Additionally, information will be collected for shallow tube well (STW) and private deep tube well (DTW) water markets for possible future intervention for attaining the objectives.

With this view in mind, the present feasibility study 'Conservation of Groundwater and Raising Its Use Efficiency and Productivity in Irrigated Agriculture in Bangladesh' has been taken under implementation by BARI, DAE, BADC and BMDA under MoA. The lead agency of the project is DAE. The main task of the project is to conduct baseline survey, mid-term monitoring and end line survey in different irrigation schemes of Bangladesh. These are largely the responsibility of the BARI.

**2. Objectives of the Study:**

The BARI component is entirely responsible for field level survey works. Where the following objectives has been attempted to be addressed:

(i) Assist in policy formulation for transition from a low-efficient, low productive and wasteful irrigation system to one with higher productive, higher efficient and less wasteful system;

(ii) Conduct a socio-economic, institutional and technical survey to understand the effectiveness of five element of a proposed necessary interventions (volume basis water charge, individual smart card, AWD technology, supply-side efficiency, community-based water management) for groundwater conservation, raising water use efficiency and water productivity in BADC and BMDA deep tube well (DTW) areas.; and

(iii) Conduct survey on shallow tube well (STW) and private DTW schemes to make water markets more efficient and productive.

**3. Brief Outline and Scope of the Study/Survey**

The study has 4 components, viz., a BADC component and a BMDA component both of which relate to ground water abstraction using DTWs for irrigation; a third component on STW which is predominantly in the private sector. The fourth component, also in the private sector, is a survey on private sector DTWs. Each of these is briefly described below:

**3.1 BADC Component**

Sample of DTWs: Total 7 (4 with buried pipes, 2 without) and a solar-based DTW as described below - all to be chosen strictly on a randomized control basis:

i) Two DTW sites with (existing) buried pipe + new technology (AWD)+ individual smart cards community action;

ii) DTW site without buried pipe + new technology (AWD) + individual smart cards +community action;

iii) Two DTW with buried pipe + manager-controlled smart cards but no new technology nor community action; and

iv) One DTW without buried pipe + manager-controlled smart cards but no new technology nor community action.

**3.2 BMDA Component**

In this case, as claimed by BMDA all DTWs have buried pipes and smart cards and hence these cannot be used for categorization. Also, all are electrified DTWs and hence no categorization by fuel is necessary. So, two categorizations are used, by location, high and low Barind and also by individual or manager-based cards. The proposed sample design is as follows:

Total sample number: 8 DTW sites (4 in high and 4 in low Barind areas);
i) Two DTWs with present volumetric water charging, individual smart cards and new technology (AWD) + community action in high Barind;
ii) Two DTW with present volumetric water charging, individual smart cards and new technology (AWD) + community action in low Barind;
iii) Two DTWs with present water charging and manager-controlled smart cards + new technology (AWD) but no community action in high Barind; and
iv) Two DTW with present water charging and manager-controlled smart cards + new technology (AWD) but no community action in low Barind.

It must be noted here that community action will be focused activities for engaging the community for individualized smart cards which facilitates AWD adoption and for collective action as AWD sometime needs some kind of land leveling. These two will be the focus of community action. However, in certain localities, people may wish to get help related to other matters relevant to crop production and post-harvest activities. In such cases, efforts will be made to provide help to the people.

It must be noted that while the above is the proposed design, the initial investigation based on benchmark surveys and discussion with local people and officials may change the actual sample characteristics. Whatever the sample characteristics, all will be chosen (in case of both BADC and BMDA) on a randomized control basis for statistical rigor.

In case of DTWs, it is expected that all farmers under a chosen DTW will be under the pilot and therefore, the benchmark and end surveys will have to have sample size representing all farmers which may be around 100 or so at most under each. This will make the total sample size to be around 1500 or so for DTWs under BADC and BMDA.

**3.3 STW Survey Component**

STW groups are small, at most 10 farmers or so. It is intended to survey only the diesel run STWs as this is the major fuel used. It is also intended to look at behavior of farmers both under cash and kind payments. It is suggested therefore that the survey be conducted among roughly 500 farmers which will entail soliciting information from 50 STW groups and 50 water seller farms.

**3.4 Private Sector DTW Components**

Private sector DTWs have command areas roughly half of those in the public sector as these are smaller in capacity. It is intended to survey 10 such DTWs which may have some 500 farmers under their command areas.
The actual samples varied somewhat due to field conditions and been reflected in the results of the survey (see later).

**4. Water Resources Scenario for Irrigation Purpose**

The Government of Bangladesh is implementing irrigation and water management strategy "to increase production per unit land, unit of water and unit of time", where most of others countries are planning for "more crop with less drop'. Agricultural practices in Bangladesh are controlled by hydrological cycle. Therefore, farmers need protection and inefficient support against: (i) flood in wet season; (ii) irrigation in dry season; (iii) supplemental irrigation in wet season; (iv) saline water intrusion in coastal area; (v) arsenic contamination of groundwater for all over the country; (vi) drainage in wet and dry season; (vii) water related hazard (storm and cyclone surge) in the coastal belt; and (viii) river erosion. In addition to these natural phenomenons, there are man-made interventions. Farmers are facing all the above constraints and thus, needs support from professionals and the government for producing enough food grains to make the country self sufficient.

**4.1 Groundwater Scenario**

**a) Groundwater Source and Conservation:** Bangladesh receives annually about 7, 95, 000 cubic meter of water through surface flow and about 2 meters from rainfall (BMD, 2000). Rain water and part of surface flow during later part of monsoon can be stored in low-lying area, smaller rivers, irrigation and drainage canals and ponds for subsequent use during dry season crop production.

Bangladesh has river area of 12, 790 square km of which about 1,890 square km have a width from 25 to 100 meter (WARPO, 2000). These narrow rivers can be converted in to temporary water reservoirs of about 1, 89,000 ha with rubber dam or any other suitable water conservation structures. Water conservation in the narrow rivers, irrigation and drainage canals during the lean period (November to May) could be stored water about 1, 92,000 (1, 89, 00+2,000+800) ha. With about 01meter depth, these water bodies can be used for fish culture in addition to their normal use and also help increasing in water conservation and storage capacity of the country. If these water bodies can be used in a planned way and thus, can contributes to the groundwater recharge and facilities additional irrigation development during the dry season and also contribute better environment.

**b) Groundwater Availability:** Groundwater is the largest store of fresh water that provides household drinking, irrigation and industrial water supplies globally (Taylor et al., 2013). In Bangladesh, approximately 32 $km^3$ of groundwater is withdrawn annually of which 90% is used for irrigation, and 10% for domestic and industrial purposes combined that is equivalent to 4% of global groundwater withdrawal (Hanasaki et al., 2018). About 98% of drinking and 80% of dry-season irrigation water supplies come from groundwater at shallow depth (<150 m below ground level, bgl) (Shamsuddin, 2018). However, the sustainability of groundwater resources is threatened by hydrological and socio-economic factors such as poor water quality, over abstraction, inadequate governance, and impacts of changing climate. Effective management of groundwater resources is critical in meeting national and international agenda for improved public health, economic development and poverty alleviation (Conti et al., 2016).

**c) Groundwater Status and Dependability:** Groundwater covers 73% of the irrigated area in Bangladesh of which 54% is irrigated with shallow tube wells (Minor Irrigation Survey Report, 2020). Fortunately, whatever volume of groundwater is pumped during dry season is almost fully recharged during wet season except in Dhaka and Gazipur cities. In these areas, groundwater withdrawal rate is higher than recharge rate. Therefore, judicious use of groundwater is recommended for these areas.

**d) Groundwater Recharging:** Rain water is the principal source of groundwater recharge in Bangladesh. Flood water which overflows the river and steam banks also infiltrates into the groundwater. Water from permanent water bodies (rivers, canal, wetland, ponds and irrigated field etc.) which lie above the water table also percolates to the groundwater. The greatest scope of recharge is within the coarse grained sediments and the least is within the fine grained sediments like clay. The groundwater flows generally from north to south. The BWDB-UNDP study calculated potential recharge using a hydrological balance where runoff was estimated to be 20% - 40% of annual precipitation. In Bangladfesh, the net recharge is higher in northwestern (Dinajpur district) and western parts (Rajshahi district) than southern (Khulna district) and eastern parts except Comilla district. The net recharge is higher (300 mm to 600 mm) along the rivers Brahmaputra and Ganges followed by north western parts of the GBM delta ranges from 250 mm to 600 mm. Therefore, steps should be taken to use harvested rainwater to recharge aquifers. Community rainwater harvesting ponds may greatly improve the groundwater position.

**e) Groundwater Use in Coastal Area:** In the coastal area, about 90% of the area remains fallow during the dry season (December to May). It is believed that groundwater in the coastal area is saline and may not be suitable for irrigation. But experience from Khulna and Satkhira area opened opportunities of using groundwater (withdrawn from certain deep layer) for crop production and drinking purposes. However, intensive investigations are needed as saline water intrusion may cause havoc. Conjunctive use of water will provide additional development alternatives. In several locations of Barisal region water is not saline and can be used for irrigation.

**f) Groundwater Quality:** The country depends on intensive withdrawal of groundwater for irrigation, industrial and household purposes. Quality deterioration of groundwater due to contamination of arsenic, iron and heavy metal has aggravated safe water availability for drinking and irrigation purposes. In Bangladesh, 60 out of 64 districts are affected by arsenic contamination. But the extent of contamination varies from area to area and entire area of a district is not affected. It was observed that arsenic concentration started at the beginning of the dry season (December/January), which was <0.05 ppm, concentration gradually increased to > 0.05 ppm by the end of dry season (May/June) but reduced again to <0.05 ppm after the rainy season. Research findings indicate that except aroid, crop production is not affected by irrigation water where arsenic level is below 0.05 ppm.

**g) Groundwater Versus Surface Water Irrigation:** Most of the groundwater based irrigation through tube wells and part of surface water irrigation through low lift pumps (LLPs) are operated and managed by private sector which cover about 90% of the present irrigated area. The remaining 10% of the irrigated area is covered by public agencies BWDB and LGED but mostly by BWDB using surface water through lift cum gravity irrigation systems. The lift cum gravity irrigation presently covers about 0.4 Mha against facilities created by BWDB for about 1.3 Mha (BWDB, 20200 which indicates utilization level is about 30%. Unfortunately, most of the irrigation facilities in Bangladesh are operating at about 50% of their rated capacities irrespective of private or public operations (Ghani, 1996).

**h) Groundwater Irrigation Supply:** Since 1960's, groundwater has been used extensively as the main source of irrigation water supply. About 79% of cultivated land is irrigated with groundwater (Mojid et al., 2019) and remaining 21% with surface water. The groundwater resource is one of the key factors in making the country self sufficient in food production. Currently, 35,322 DTWs and 15, 23, 322 STW are operating in Bangladesh to provide water for irrigation (CSISA-MI Report-2).

### 4.2 Number of Irrigation Device and Irrigated Area (ha)

During the 2019-20, the number of DTW, STW and LLP were 35,322, 15,23,300 and 1,70,570, respectively covering 52,55,000 ha irrigated area. In case of DTW, STW and LLP the actual command area were 32.29 ha, 2.28 ha and 6.47 ha, respectively against the standard command area of 40.00 ha, 5.00 ha and 28.00ha, respectively.

**Table-1. Irrigation device-wise Irrigated Area and Irrigated area per Device**

| Year | Irrigated area (000 ha) | | | Irrigated area per device (ha) | | |
|---|---|---|---|---|---|---|
| | DTW | STW | LLP | DTW | STW | LLP |
| 2009-10 | 773 | 3,337 | 964 | 23.50 | 2.34 | 6.42 |
| 2010-11 | 719 | 3,505 | 1,010 | 21.36 | 2.26 | 5.82 |
| 2011-12 | 759 | 3,418 | 1,084 | 22.23 | 2.28 | 6.12 |
| 2012-13 | 934 | 3,242 | 1,034 | 26.45 | 2.13 | 6.07 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 2013-14 | 877 | 3,279 | 1,084 | 24.33 | 2.10 | 6.33 |
| 2014-15 | 962 | 3,235 | 1,107 | 26.30 | 2.08 | 6.62 |
| 2015-16 | 1,194 | 2,955 | 1,165 | 32.29 | 2.08 | 6.72 |
| 2016-17 | 1,063 | 3,079 | 1,188 | 28.60 | 2.20 | 6.73 |
| 2017-18 | 1,073 | 2,982 | 1,221 | 28.57 | 2.19 | 6.72 |
| 2018-19 | 1,076 | 2,994 | 1,247 | 28.59 | 2.21 | 6.67 |
| 2019-20 | 1,084 | 3,001 | 1,270 | 29.30 | 2.15 | 6.35 |
| Standard Command Area/Device | | | | 40.00 | 5.00 | 28.00 |

**4.3 Conjunctive Use of Water:** Water resources development plan should be developed as per agro-ecological regions of Bangladesh. The national irrigation plan should be to maximize utilization of rainfall, surface and groundwater through conjunctive use of these resources. Water use priority should be to utilize rain water to the extent possible then use of surface water from nearest river/canal/ponds. If rain and surface water cannot meet demand of crops then use groundwater, so that crop production does not suffer from water. This way of scheduling water use from rainfall followed by using surface water and further followed by groundwater for optimum crop production is called conjunctive use of water.

**4.4 On-farm Water Management:** Most of the cases traditional on-farm water management is practicing for crop irrigation. Field experiments/demonstrations on on-farm water management should include crop demonstration programs over the country (2 to 3 ha in each Upazila). Demonstration of improved technology programs selected and managed by participating farmers and organized by Upazila Agricultural Extension Coordination Committee (UAECC) since this is an interagency coordinating forum. Upazila based annual crop production plan considering farmers 'needs and profitability, soil types and water availability should be developed and implemented. Training will also be provided to improve capacity of upazila level staff of DAE and others. Emphasis will be given on on-farm water management, pump operators and mechanics and to farmers (including training of women in seed processing, compost making, and homestead gardens improvements). This will help in increasing crop production and soil health management under irrigated condition.

**4.5 Groundwater Based Irrigation Cost Effective:** It is reported that both DTW and STW lifting groundwater and large-scale canal irrigation systems are operating at about 50% or less than their efficiency level. Over the years, STWs were operated at 50% of their rated capacity and irrigated 2.6 ha against potential of 5 to 6 ha.. DTWs were also operated and covered on an average 25 ha against rated capacity of 40 ha. Experiences indicate that over all irrigation efficiency levels of tube wells and canal irrigation systems can easily be increased to 75% and 70%, respectively. That means another 25% area could be brought under irrigation with existing irrigation facilities by increasing efficiency of the systems. therefore, performance improvement of existing irrigation systems can be one of the ways of making the systems cost effective.

**4.6 Change Water Use Pattern:** In Bangladesh, irrigated agriculture means irrigated rice cultivation. Diversification of crops under irrigated conditions may make agriculture more profitable and may also reduce pressure on irrigation facilities, since water requirements for non-rice crops are much less than irrigated rice cultivation. Crop diversifications are becoming popular but market variability still discourages cultivation of non-rice crops.

Irrigation management for rice cultivation should be revisited as alternate wetting and drying (AWD) of rice field brings about 25% additional areas under cultivation without yield reduction with same amount of water delivery against traditional irrigation (continuous standing water). This will make irrigation systems cost effective. However, motivation of pump owners is a precondition for expansion of AWD. Pump owners used to have contractual arrangement with farmers for delivering irrigation water for area basis (bigha/acre) not by volume of water or number of irrigations requirement for growing period of crop. Therefore, benefit of water saved by adopting AWD goes to the favor of pump owner not of the farmers. Government agencies and NGO representatives should arrange for compromise solution among farmers and pump owners.

4**.7 Impact of Climate Change on Water Resources:** The government of Bangladesh has recognized climate as an important issue for over all of development of water resources. In recent years, the frequency of extreme climate events, such as floods and cyclones has increased worldwide. The most damaging effects of climate change are floods, salinity intrusion, and droughts that are found to drastically affect crop productivity. Climate change induced challenges are: (i) scarcity of fresh water due to less rain and higher evapo-transpiration in the dry season; (ii) drainage congestion due to higher water levels in the confluence with the rise of sea level; (iii) river bank erosion; (iv) frequent floods and widespread drought; (v) increased salinity and (vi) degradation of biodiversity. Thus, climate change policy, particularly adaptation is a part of the development policies of the country.

**4.8 Water Resources in Northwest Region:** Northwest region covers the area under present Rajshahi and Rangpur divisions and greater Kustia and Jessore disticts (WARPO, 2000). Most part of this area has low rainfall but fewer subjects to flood damages. The net cultivable area (NCA) of this region is about 2.94 Mha and has a dependable groundwater source and thus, can be brought under double/triple cropping with conjunctive use and improved management of water resources.

**4.9 Water Resources in Barind Tract:** High temperature in the summer with low humidity and rainfall has distinguished Barind tract of about 1.4 Mha.. Groundwater is a dependable source of irrigation in the area and can cover about 60% of the Barind tract but groundwater level goes below suction limit especially during the dry months. About 57%of cultivated area is irrigated (BMDA, 2021). Surface water conservation is possible in the rivers, low-lying areas including *beels* and ponds. There are about 32,000 pond in the BMDA project area and about 70,000 in the entire BMDA area. These ponds after re-excavation can be used for accumulation of excess rain water and can be subsequently used for supplemental irrigation, household uses and fish culture. Bank and adjacent land around the ponds can be used for a forestation and vegetable cultivation, which can further help in poverty reduction in addition to water conservation.

**4.10 Water Productivity (WP) in Irrigated Boro Rice:** Water productivity physical accounting of water with crop yield to give an indication of how much value is obtained from the usage of water. Three different types of crop-water productivity – physical, economic and non-economic are usually distinguished for different agricultural systems. The most popular is the physical water productivity; define as the mass of product per unit of consumed water or actual crop evapotranspiration ($ET_c$) and usually expressed in kg $m^{-3}$. However, for most practical purposes, WP is also estimated considering the quantity of water supplied to the field (irrigation) and total water available in the field (irrigation plus rain fall). Economic water productivity is the standardized gross or net value of the product or net benefit per unit of water consumed, while non-economic (e.g., social or environmental) water productivity indicates the net social benefits per unit of consumed water.

It was observed from field study in the NW of Bangladesh conducted by Mainuddin et al., 2020 that average water productivity was 0.67 kg $m^{-3}$ and 0.64 kg $m^{-3}$ based on total available water (rain fall plus irrigation) in the fields, 0.80 kg $m^{-3}$ and 0.95 kg $m^{-3}$ based supplied irrigation, and 1.60 kg $m^{-3}$ and 1.78 kg $m^{-3}$ based on estimated actual crop evapotranspiration (ET) during 2015-16 and 2016-17, respectively. They also mentioned that in the STW areas, water supplied by the farmer was very close to actual requirements, but in DTW areas had some over application. The average total amount of water available in the field to grow one kilogram of rice was 1,606 liter (L). The average irrigation water supplied to the field was

1,402 L $kg^{-1}$. However, not all water supplied to the rice plots are consumed by the plants. Actual crop evapotranspiration is the real water use and based on that only 661 L was required to grow one kilogram of rice. Percolation and seepage water return to the underlying aquifer as return flow. Therefore, government policy of 'water savings' by reducing pumping of groundwater is unlikely to have any major impacts on the sustainable groundwater irrigation in the NW region.

**4.11 Water Charge and Profitability in Irrigated Boro Rice:** The North-West (NW) region of Bangladesh produces over one-third of the country's total rice despite covering 23.5% of the country's total area. It has 30% of the net cultivable area (NCA) and 40% of the total irrigated area of the country. The average cropping intensity is also higher (205%) than the country's average cropping intensity of 194%. The region is one of the major irrigated Boro rice producing area with highest average yields of rice. But the area has uncertainty to the sustainable Boro rice cultivation due to increasing cost of irrigation, fertilizers, labor and other inputs, and variation in actual yield, market price and profitability.

There was variation in paid-out costs of different activities across the locations and their share as a percentage of total costs. Total paid-out cost of production is highly dominated by the cost of fertilizer, irrigation, and harvesting (crop cutting, carrying, and threshing). These three activities accounted for 59% to 62% of the total cost. The cost of irrigation was the highest (23%) followed by harvesting (21% to 22%) and fertilizer (16% to 17%) are shown in Table-2. It should be noted that irrigation is the key. Without irrigation, crops will be low-yielding, fertilizer application will be low and cost of harvest due to low yield would be much less.

**Table-2. Share of Paid-out Costs of Different Activities for Boro Rice Production**

| **Production Activities** | **Share of total gross cost (%)** |
|---|---|
| a) Seed (including seed, nursery preparation and seedling development) | 5.0 |
| b) Land preparation (tillage) | 7.0 |
| c) Transplanting (including seedling uprooting) | 8.0 |
| d) Fertilizer | 16.0 |
| e) Weeding (including herbicide) | 7.5 |
| f) Pesticide | 5.0 |
| g) Irrigation | 23.0 |
| h) Harvesting (including crop cutting, carrying, and threshing) | 21.0 |
| i) Cleaning and Drying | 8.0 |

Source: Adapted from Mainuddin et al., 2021.

Total paid-out cost, gross benefit and gross income varied across the locations and irrigation pump types (Table-3).

**Table-3. Cost and Return of Boro Rice Production across Locations, Varieties, Pump-types, and Transplanting Dates**

| **Items** | **Total Paid-out Cost (Tk/ha)** | **Gross Benefit (Tk/ha)** | **Gross Income (Tk/ha)** |
|---|---|---|---|
| **a) Locations** (average of 6 locations) | 72,457 | 97,836 | 25,379 |
| **b) Rice Varieties** ( average of 6 varies) | 72,277 | 97,510 | 25,233 |
| **c) Pump-types** | | | |
| i) DTW (electric) | 77,078 | 94,519 | 30,561 |

| | | | |
|---|---|---|---|
| ii) STW (electric) | 70,975 | 107,640 | 25,317 |
| iii) STW (diesel) | 71,519 | 96,291 | 23,000 |
| iiv) Solar Power | 68,029 | 129,741 | 61,713 |
| **d) Transplanting Dates** | | | |
| i) January | 72,780 | 97,219 | 24,439 |
| ii) February (1-14) | 73,683 | 100,579 | 26,896 |
| iii) February (15-28) | 63,971 | 83,995 | 20,025 |

Source: Adapted from Mainuddin et al., 2021.

Tube well type and power source-wise water pricing is shown in Table-4

**Table-4. Water Pricing System for Boro Rice Production**

| **Locations** | **Tube well Types** | **Power Sources** | **Water Pricing System** | **Discharge Capacity (L/s)** |
|---|---|---|---|---|
| Thakurgaon | DTW | Electric | Meter system, Tk. 110/hour | 58.0 |
| Kaharul | STW | Electric | Fixed rate, Tk. 14,280/ha | 13.5 |
| | STW | Diesel | Fixed rate, Tk. 17,290/ha | 8.9 |
| Mithapukur | STW | Electric | Fixed rate, Tk. 9,880/ha | 14.8 |
| | STW | Diesel | Pump charge Tk. 5,930/ha to 7,900/ha plus farmers bring their own fuel | 9.4 |
| Sherpur | STW | Diesel | Fixed rate, Tk. 22,230/ha | 7.2 |
| Ishardi | STW | Diesel/Electric | Crop share. Pump owner takes 25% of crop | 14.0 |
| Tanore | DTW | Electric | Meter system, Tk. 120 to Tk. 140/hour | 18.5 |
| Badarganj | STW | Solar | Fixed rate, Tk. 17,290/ha | 9.0 |

Source: Adapted from Mainuddin et al., 2021.

## 5. Need and Justification of the Study

The need for the study arises from the fact that the water charging system by and large is area-based which does not provide any incentive to farmers to save water even when crop water-saving technologies are available. However, water is already scarce by season and over space and on a per capita basis Bangladesh is water-deficient and is expected to be more so in future. All efforts should therefore be made to lower water use for irrigation by raising its productivity and efficiency in use for possible reallocation to other legitimate purposes. This calls for use of all available instruments for doing so. The present project is a modest attempt to understand if and how this may be done for irrigation using ground water.

The EPI study came up with several recommendations based on its findings which provide the rationale for the present study undertaking. These are as follows:

### 5.1 Water Use Practices and Water Charging Systems: Case for Water Demand side Intervention

In Bangladesh agriculture, it is common knowledge that water use in rice production is more than optimal. This is mainly due to two basic reasons, viz., the perception and practice of farmers that rice fields need to be kept flooded for a long period over the crop's life-cycle for a good yield (we see later that this belief is no longer held so widely); and secondly that when water is used for irrigated rice production (which accounts for around 60% of present domestic rice output), water is more often than not charged for and sold by area of land irrigated, no matter what volume of water is applied to the field. Scientists in Bangladesh proved time and again through experiments on farmers' fields that several crop water saving technologies such as Alternative Wetting and Drying (AWD), System of Rice Intensification (SRI) and Dry Seeding of Rice (DSR) can save substantial amount of water without affecting yield of rice. And most agriculture officials in the upazilas and employed by the Department of Agricultural Extension (DAE) know about these methods particularly AWD and some have also tried to introduce them on their own but with mixed success. This is because farmers in most cases have to pay the charges for irrigation water which is fixed by area no matter what the quantum of water applied is.

The EPI survey of world literature and practices has shown that farmers are amenable to conservation of water only if the charges are made by volume of water applied. In Bangladesh, there are experiences of charging for irrigation water using deep tube wells (DTW) by volume mainly in the BMDA-run DTW areas and to an extent also under BADC-run DTW areas. In such cases smart cards are used to run the DTWs and monitor the volume of water that is abstracted.

In some cases these cards may be owned individually by farmers, in some other cases, these may be actually held by managers or operators who use them for running DTWs when a particular farmer wants to irrigate his/her field. The reason cited for not holding cards individually is the financial constraints faced by the farmers in purchasing and charging the card for payments.

The implication of individual holding of smart cards is that this provides the farmer direct control over his/her use of water. Recent experience based on large field surveys shows that farmers accept new crop technology which saves water not simply if *water charging system is based on volume but additionally and more importantly also if smart cards are owned and operated individually, not by some managers* as is often observed in some cases. Obviously, the individual smart cards by allowing farmers to control use and abstraction of water allow them fine tune its use as well as lowering costs. It is therefore imperative that the ideas be widely translated into practice.

While there are some domestic examples of volumetric pricing, as indicated earlier, it is less frequent in case of operation of BADC-run DTWs while in some areas of BMDA where this is universal, reportedly there are deviations from the official norm of holding individual cards. One needs to not simply understand why this is so and what its impact on actual use and abstraction of water, but also if the global best practices and in-country experiences can be used for conservation of water, raise its productivity and maintain environmental integrity. Indeed, it may hypothesize that individual holding and operation of smart cards may actually lower farmers' cost of irrigation and thus be acceptable to them provided an enabling social environment may be created.

**5.2 Supply Side Efficiency**

Apart from the introduction of crop water saving technologies and a revised system of charging for water for BADC and BMDA DTW operations, two more interventions are necessary. One is the use of buried pipes for transmission of water from the DTW site to the vicinity of the farmers' field. This saves the loss of water due to percolation and evaporation which is estimated to be at least 30% of the total water abstracted in its absence. This is a clear and simple case of investment understood by all agricultural engineers. Unfortunately, this is not yet the case in all cases of DTW areas. One needs to understand the differential behavior of farmers regarding crop water use in such cases.

The other important aspect of buried pipe is that it reduces the need for whole catchment areas of farmers to adopt AWD, as the water transmission is managed on a field by field basis and eliminated water supply via neighboring fields.

### 5.3 Community as the Conduit for Intervention

Ultimately, it is the farmers in a community who finally are the final judges and executors of all interventions as described above. A successful intervention regarding the introduction of crop water saving technology and the changes in the water charging system depend critically on their behavioral attitudes and their changes. There are reportedly water user associations (WUA) in DTW areas though perhaps in different levels of activation and performance. The farmers' behavioral changes through community actions involving the WUAs become the fulcrum for the acceptance of the proposed interventions and their practice by the farmers and thus the ultimate success of the pilots. This becomes important because the acceptance and use of water saving crop technology in some cases may need collective action by farmers having contiguous plots of land. Similarly, a change from a few smart cards holding by managers to that of many by individuals also necessitates community deliberations and actions. How this may be done and what are the financial implications for individual farmers need to be clearly understood and acted upon by the farmers as a group.

The desired changes however may not come automatically but through the actions of change agents. Two types of change agents are envisaged here. While both must complement and coordinate with each other, one group should be focused on the adoption of crop water saving technology while the other may be well-versed in water related issues including monitoring and evaluation. For both the idea is to engage specific public bodies as change agents. It may be noted here that one intervention must be a system of training for trainers drawn from these two types of organizations and also training of farmers for management of water abstraction as well as application in the field.

### 5.4 Case of Shallow Tube Wells

So far, the discussion had been in terms of water conservation under DTW-based ground water irrigation. In Bangladesh while the dependence on ground water for irrigation is very high, in fact, it is the shallow tube wells (STW) which are the backbone of the system as these accounts for nearly 70% of such irrigated areas. The intervention in case of STW for conservation of water is, however, quite tricky as here the system is fully dominated by a private agent-based market where water charges are by area, much higher than in case of BADC/BMDA DTWs and the interests of the buyers if they choose to lower water usage and thus lower charges conflicts with the financial interests of the water seller as his/her income will go down. Some ideas related to a Payment of Ecosystem Services (PES) has been thought about to resolve the situation and is known to be in practice under various circumstances of water management in other countries. But it cannot be put in practice even for piloting right now because of limited rigorous information on behavior of farmers (both sellers and buyers) in the water market and consequently of how there may be a socially optimal understanding of mutuality of interests of the water buyers and water sellers. It is therefore proposed to collect pertinent information first before a pilot may be designed for the purpose.

### 5.5 Case of Private Sector DTWs

The private sector DTWs portrays a situation similar to the STWs in the private sector. Issues are similar but may be a bit more complex as the level of investment by water sellers is much higher and the command area is also much larger making it perhaps an even more complex system. But little so far is known about them. Some of these DTWs have been surveyed to find out how these operate and if there are avenues for better water-related performance in such cases.

**5.6 Scaling up a Successful Pilot**

Finally, it may be noted here that under the unfolding scenarios of climate change, water is likely to be scarcer both temporally and spatially than at present while there is an imperative also to lower greenhouse gases, however small, on the part of Bangladesh as this is its official global commitment. Conservation of ground water thus becomes both an adaptation and a mitigation measure (through lowering energy use for lowered abstraction of wateras well as lowering metahne emission due to moving away from deep flooded rice). If the pilot experiments are successful in conservation of water, this will open up major opportunities for raising major grant or low interest funds from the Green Climate Fund (GCF) for large scale application of the lessons learnt for water management. Indeed, so far as is known, no country yet has submitted proposals similar to that described above and thus may become a novel idea to GCF.

**6. Output**

i) A baseline survey of BADC and BMDA deep tube wells (DTWs) and a corresponding analytical report;
ii) A STW survey and corresponding analytical report;
iii) A private sector DTW survey and corresponding analytical report;
iv) End line survey of BADC and BMDA deep tube wells (DTWs) and corresponding analytical report with recommendations based on earlier and end line survey as well as incorporating STW and private sector DTW analysis insights;
v) A mid-course monitoring and progress report;
vi) Training of approximately 30-35 officials;
vii) Training 1500 farmers;
viii) Distribution of individual smart cards to approx 300 farmers;
ix) Formation/activation of Water Users Association in 8 DTW areas; and
x) 4 workshops/seminars for dissemination of project information and findings of surveys.
As it turned out rather than having separate reports fro each type of irrigation device, a comparative report is far more illuminating and thus we have done it that way in this report.

**7. Implementation Arrangement**

There is a Project Management Committee (PMC) to guide the implementation of the study in the field and periodically assess its progress. This is chaired by an official of the MoA. DAE is the lead agency. As a lead agency it will coordinate all activities in the field as well as report to the PMC. Additionally, DAE will also conduct the social mobilization part of the study project. It will contract out BARI for the survey (baseline and end line survey) activities. DAE will further coordinate its field work in consultation with BADC and BMDA as appropriate as in case of distribution of smart cards in areas where these will be necessary. The training of officials will be coordinated by BARI with the help of DAE and staff drawn from DAE Farmers will also be trained in the same manner.

## Chapter II: Survey Methodology

**2.1 Sampling Method:** Multi-stage sampling method has been used for data collection for the study. Firstly, 23 upazilas of 15 districts have been selected from 7 divisions using Stratified Random Sampling method. In the second phase, total 2,500 respondents of DTW and STW users have selected purposively. Samples have collected from the selected area using multi-stage random sampling methods. The sampling structure is shown below:

**Table-1: Sampling Selection Structure**

| Stage-I | | Stage-II | | Stage-III | To be conducted online based interview of 2,500 respondents using electronic device TAB (DTW under BMDA: 800; DTW under BADC: 700; STW Areas:500; and Private Owned DTW: 500) |
|---|---|---|---|---|---|
| Division # 07 | ➢ | Districts # 15 | ➢ | Upazila # 23 | |

Thus, the total sample sizes of the survey activities are as follows:

| **Irrigation Device and Operational Status** | **Number of Sample** |
|---|---|
| i) DTW under BADC | 700 |
| ii) DTW under BMDA | 800 |
| iii) Private Owned/Operated STW | 500 |
| iv) Private Owned/ Operated DTW | 500 |
| **Total** | **2,500** |

**2.2 Selection of Sampling Area:** The Feasibility Study on "Conservation of Groundwater and Raising Its Use Efficiency and Productivity in Irrigated Agriculture in Bangladesh" is being implemented in all upazilas of 23 districts in 07 divisions. The divisions of the sample areas based on the upazila are shown in Table-2.

**Table-2: List of Selected Sample Areas**

| **Selected Division** | **Selected District** | **Selected Upazila** |
|---|---|---|
| Rajshahi | Rajshahi | Godagari and Putia |
| | Naogoan | Naogoan Sadar, Sapahar, Dhamuirhat, Niamatpur, and Porsha |
| | Chapai Nababganj | Nachale |
| | Bogura | Dhupchachia |
| | Sirajganj | Sirajganj Sadar |
| | Pubna | Irshardi |
| Rangpur | Thakurgoan | Ranisankair, Horipur and Baliadangi |
| Dhaka | Manikganj | Saturia |
| | Gazipur | Sreepur |
| Mymensingh | Mymensingh | Mymensingh Sadar |
| | Netrokona | Netrokona Sadar |
| Chattagram | Comilla | Debidder and Burichang |
| Sylhet | Hobiganj | Madhabpur |
| Khulna | Satkhira | Kolorua |
| | Jessore | Sarsha |
| **Total: 07** | **15** | **23** |

**2.3 Key Informant Interview (KII) and Consultative Meeting:** In order to better understand the issues, KII and Consultative meeting has conducted in the BMDA and BADC with the concerned Officials. Necessary guidelines have been prepared and used for this. The Project Coordinating Director and Consultants held in-depth investigative discussions with project officials and concerned persons to discuss various issues related to the project.

**2.4 Data Collections Tools:** Adequate information is required to prepare the report. Respondent-based questionnaires were prepared for the required data. These are as follows: Direct Field Survey Questionnaire (based on electronics device): one set; and KII and Consultative Meeting Checklist - one set.

**Open Data Kit (ODK)** is a free, open-source suite of tools that allows data collection using Android mobile devices and data submission to an online server, even without an Internet connection or mobile carrier service at the time of data collection. ODK is open-source software for collecting, managing, and using data in resource-constrained environments. It allows for offline data collection with mobile devices in remote areas. The submission of the data to a server can be performed, when Internet connectivity is available. It allows communities to aggregate data with full control over the collected data and the servers where this data is stored.

ODK can be applied, when a community wants to collect data with full control over the collected data. Collected data can be stored offline on the mobile device. The collection and aggregation of data from the devices can be performed with Open Source tools according to privacy concerns of the community. The community members must be able to check the source code of the client and server application for unwanted features and respect for the privacy concerns. Furthermore, if the community wants to have full administrations rights for the server backend, then the ODK infrastructure can be set up according to these requirements and constraints for privacy concerns of the community. Because ODK allows the data collection in resource-constrained environments ODK is intended to be applied for underserved population and identify their needs and community driven innovation based on the aggregate data.

**2.5 Recruitment of Enumerators and Training**: The data collection team collected data from the field level. Three-day (15-17 November 2021) training was organized for the field level staff for survey purposes and to make them proficient in the use of on line data collection kid and materials (ODK and TAB). In addition, the members of the project team also taught the trainees how to collect data from the field level using data collection materials and how to conduct real-time interviews.

**2.6 Data Management and Processing:** Considering the purpose of the research, the analysis of the required information was completed through using the Excel/SPSS program. Percentage ratio, bar charts, column charts, pie-graphs, etc were generated and prepared result based simple table.

**2.7 Reporting:** The report uses a standard format so that the results of the feasibility study activities can be easily compared with the project objectives, plans and implementation. The data obtained at the field level have been analyzed and presented in the form of both text and graphs. . The PCD informed the concerned authorities about the progress and results of the work at different stages of report preparation. The present report isa preliminary one and needs some further analysis which will be integrated with the present report for a final report which will be  final report was prepared by incorporating Technical and Steering Committee feedback.

# Chapter-III: Results and Discussions

## 3.1Realised sample of farm households

We intended to sample 1500 farm households on a randomized sample basis for BMDA and BADC. Against that target we ended up surveying 675 BADC and 774 BMDA DTW farmers making it a total of 1449 farmers (Table 1). This is more or less on target. For STWs, we ended up surveying 497 farmers against the target of 500, again on target. However, we could not find enough private DTWs to survey. Farmers under such DTWs numbered only 324 against the target of 500. On the whole except for BMDA sample which has to be by definition must be confined to Rajshahi division, all others are somewhat well-spread over Bangladesh

Table- 1 : Summary Information of the Tube Wells by Division and Irrigation Management (percent of farms)

| Division | BADC DTW | BMDA DTW | Private DTW | STW |
|---|---|---|---|---|
| Chattogram | 11 | 0 | 0 | 0 |
| Dhaka | 9.6 | 0 | 33.3 | 5.6 |
| Khulna | 21.3 | 0 | 15.4 | 10.1 |
| Mymensingh | 22.7 | 0 | 15.4 | 7.8 |
| Rajshahi | 32.1 | 100 | 35.6 | 50 |
| Rangpur | 0 | 0 | 0 | 24.9 |
| Sylhet | 3.7 | 0 | 0 | 1.5 |

Rajshahi division accounts for most, nearly 60%, of the households surveyed. The reason for Rajshahi having so many of sample households is that it includes the whole of BMDA, and a substantial parts of BADC and private DTWs as well a good number of STWs. This also provides us a good opportunity to compare performance across irrigation management types in largely similar agro-ecological situations.

**3.2 Capacity of irrigation equipment**: Irrigation equipment, particularly in case of a DTW is most likely to be of 2 cusec capacity (Fig. 1). But in case of BMDA, a good proportion of such equipment are of 1 cusec capacity. In case of private DTWs, some are of 1.5 cusec capacity.

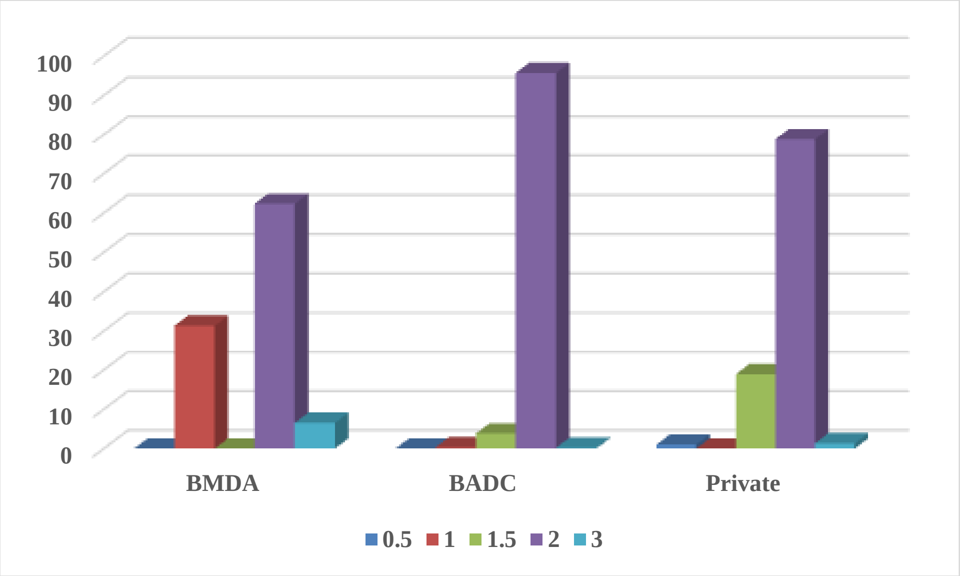


**Fig. 1: Distribution of Sample DTWs by Capacity (cusec)**
(percent of devices)

**3.3 Ownership size distribution of land:** Distribution of land ownership across farms as well as irrigation management groups are shown in Fig. 2. As is expected most farms are in size group under 1 acre. Yet, one finds some differences across irrigation management types in that in case of BMDA and STWs, and more for the former, there are not insubstantial proportion of medium land owner farmers. Thus the pattern is less unequal in such a case. For private DTWs, a quite high percentage of farmers are in the lowest group meaning that the clients here are the lowest land owning group.

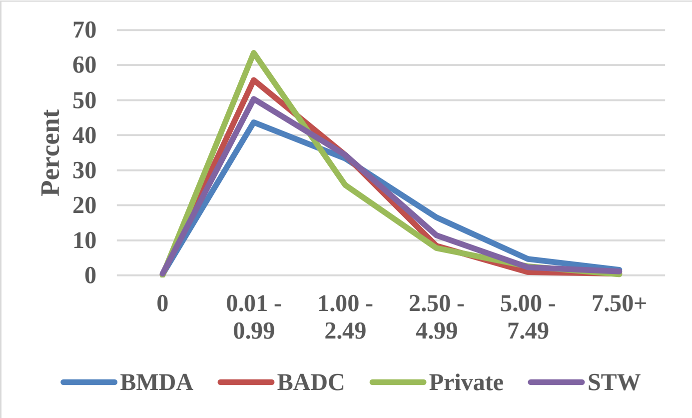


**Fig. 2: Distribution of Sample Farms by Landownership Category** (in acres) **and Irrigation Management group**

**3.4 Operational holding size distribution:** The pattern of ownership is reflected also in case of operational holding which takes care of participation in the land lease (share-tenancy, renting, mortgage etc) market. The patterns by irrigation management group are shown in Fig. 3.

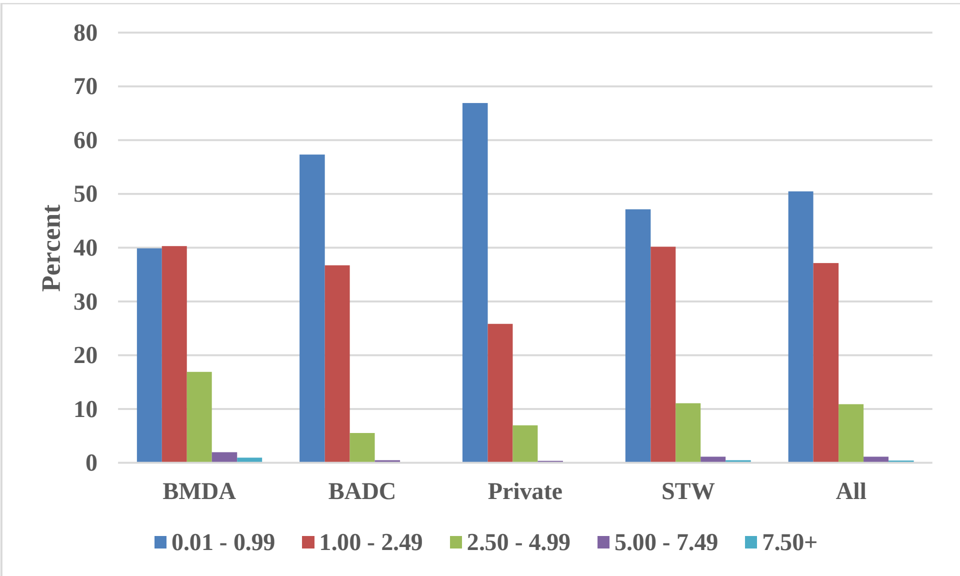


**Fig. 3: Distribution of Sample Farms by Operational Holding Size and Irrigation Management Group**

The figure shows that in case of BMDA, farm size is somewhat evenly distributed across size groups, particularly the presence of medium sized farms is noticeable as has ben found in terms of land ownership. This is much less so in case of other irrigation management groups. We will try to see in course of further analysis if such distribution has any impact on water use across farms by irrigation management type.

**3.5 Age of head of household**: Age groups of heads of household are quite similar across the irrigation management group. Hence we show them together in Fig. 4. We find that around 85% are in age groups above 30 years.

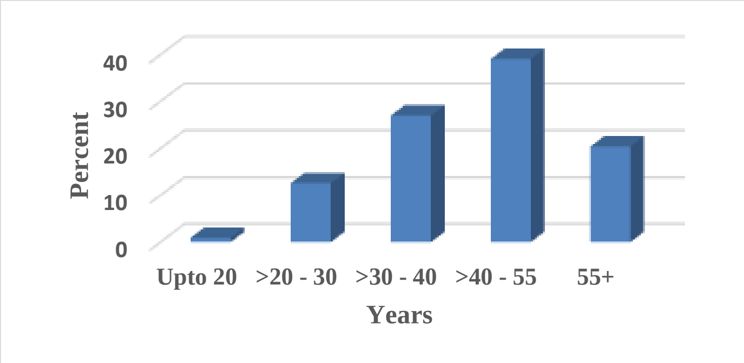


**Fig. 4: Age of Household heads**

**3.6 Family size**: Average family size does not vary much across irrigation management groups. These are 4.94 for BMDA farms, 5.20 for BADC farms, 5.16 for private DTW farms and 4.62 for STW farms. Not surprisingly, we also find that for all farms by type of irrigation management, the most frequent size is stated to be between 4 and 6. The percentage of farms of such family size are 67 for BMDA, 63 for BADC, 63 for private DTW and again 63 for STW farms. On the whole, including age groups of household heads and family size, the demographic characteristics seem to tally with general impression about Bangladesh population characteristics in the rural areas.

**3.7 Land under boro rice:** Rice during the boro season is the main crop. Within rice, HYV boro is the most cultivated variety. More than 97 percent of cultivated land under boro rice is of HYV. Local boro is practically absent while Hybrid boro accounts for no more than 2% of cultivated land. By farm size, of course, the actual land under boro varies, but the pattern remains the same in that it is HYV boro which holds sway above all other varieties.

**3.8 Water management and use by irrigation management groups**

One major aspect of the present survey had been to find out the mechanisms under each for water management, pricing and advantages and disadvantages of the specific irrigation management practices. Below we provide an analysis of what farmers say about the different management practices which may help policy makers to decide on future course of action for better irrigation management particularly as it relates to conservation of water.

*3.8.1 Irrigated area changes during the immediate past boro season*

One of the first questions that had been asked if during the last boro season, the irrigated area was less than the cultivable operational holding. It has been found that practically in all cases, either this was the same or probably have increased somewhat. The proportion of farms replying so varied from 100% for BADC to 93% for BMDA.

*3.8.2 Trend in change in area under irrigation over last 4/5 years*

Indeed, it has been found that over the 4/5 years prior to the survey, practically in all cases there had been a rise in the area under irrigation varying from 94% for BMDA to 100% for private DTWs.

*3.8.4 Reasons for increase in area under irrigation for boro rice*

The results of the answers to the question vary by irrigation management for DTW. But one fact stands out which is availability of required amount fo water and timely availability. Given these, there seems to be some differences between say BADC and other DTW farmers. While DTW farmers under BADC do not think that the water charge is not so high, BMDA and private DTW farmers seem to differ somewhat. On the other hand, in case of BADC farmers, field management do not seem to be so good as in case of BMDA and private DTWs. The results are shown in Fig. 5.

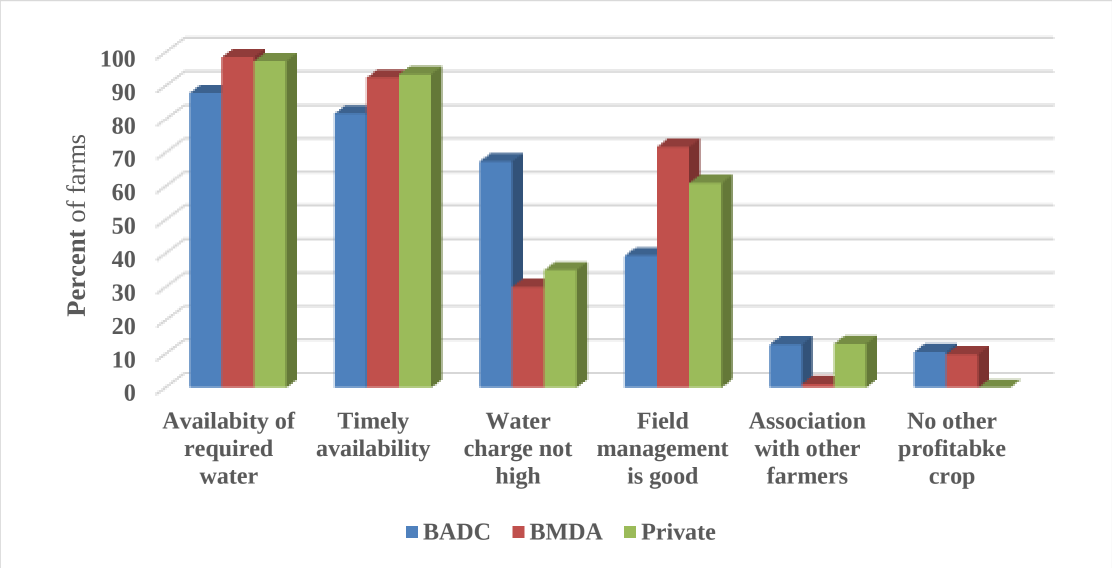


**Fig. 5: Reasons for increase in area under irrigation over last few years**

*3.8.5 Reasons for decrease in area under irrigation*

There had not been much diminution in area under irrigation over last few years. Whatever decrease has taken place, had been fund to be only in case of BMDA and mostly either because price of water is high (68%) or non-availability when required (64%). Inadequate supply has been cited by 48% while higher profitability of other crops has been cited by 36% of BMDA farmers who decreased their boro area under irrigation.

*3.8.6 Reasons for changes in area under irrigation under STW*

The reasons for area changes under irrigated boro under STWs, seems to corroborate broadly the findings under DTWs. Ninety-six percent of STW water users increased their area under irrigation mainly due to availability of required amount of water (33%), water availability on time (33%) and good field management (24%). Not so high water charges have been cited by under 10% of STW farmers.

*3.8.7 Water availability during season*

Water had been available during the whole season practically in all cases under different irrigation management varying from 96% under STWs to nearly hundred percent for BMDA DTWs.

*3.8.8 Water pricing methods and their advantages and disadvantages*

One major issue that the present survey wanted to find out is the variety of water pricing methods and the advantages and disadvantages of such systems. First, the pricing methods. These are shown in Fig. 6.

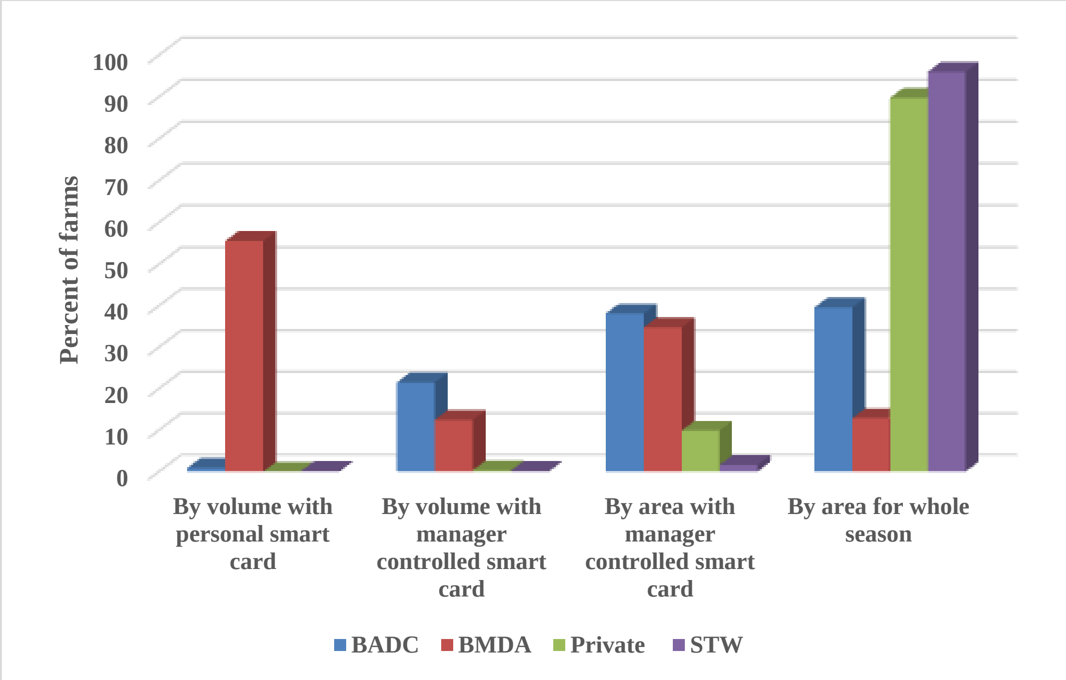


**Fig. 6: Water pricing methods by irrigation management type**

The figure clearly shows that volumetric pricing with own smart cards, although practiced most in BMDA DTWs, manager controlled smart cards for volumetric and more by area is the preferred method. The latter is certainly true for all non-BMDA DTWs. For private DTWs and STWs, this is quite understandable. However, this shows, that despite attempts, the BADC had not been able to limit or remove the stranglehold of managers/operators on ordinary farmers. Indeed, even for a small percentage (nearly 13%), pricing by area is practiced also under BMDA. Question is why such differences? For this we asked farmers regarding the advantages and disadvantages of the pricing methods.

Fig. 7 shows the perceptions of farmers based on their experience of *water use under volumetric pricing*. We show the results for only BMDA as in all other case, volumetric pricing is not practised that much. We find that three advantages have been cited by farmers. First, water use is lowered but without any negative effect on yield (57.4%) followed unsurprisingly by lower cost of water as usage is lower and thirdly farmers' capacity to control application of water (83%). As is clear all actually lead to lower use and lower cost ultimately and tis is facilitated by farmers/ capacity to control water application.

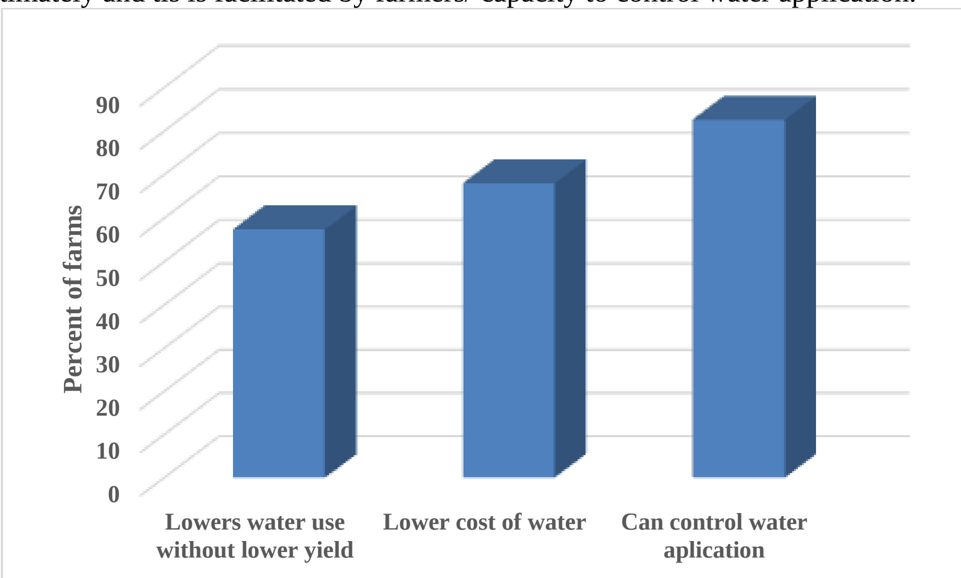


**Fig. 7: Advantages of volumetric pricing with own smart card**

*What about the disadvantages*? These in one way or other relate to perceived cost of smart cards, its safe keeping both cited by nearly 70% of farmers and cash constraints for topping up the card (nearly 30%). Note also particularly the hassle of regular checking of water level in the field which is cited by about 28% if farmers. Dependence on others for operating pumps is not a major issue.

*For manager controlled smart cards*, for both BMDA and BADC, the overriding concern is saving of hassles be it on the field, topping up of cards or other technical issues. Fig. 8 demonstrates these issues clearly. However, we find that there is a difference between BADC and BMDA farmers. For the latter, topping up by managers is a great help (89.5%) as farmers often may not have ready cash for topping up. Adequacy of water supply is no problem in either case. Finally, the problems of administrative or technicalities can be handled by the managers. What all these mean is that people want to have lower cost water but also as little hassle as possible which in a way raises the indirect cost of water by requiring the farmer to be more involved as happens with volumetric pricing with own smart cards.

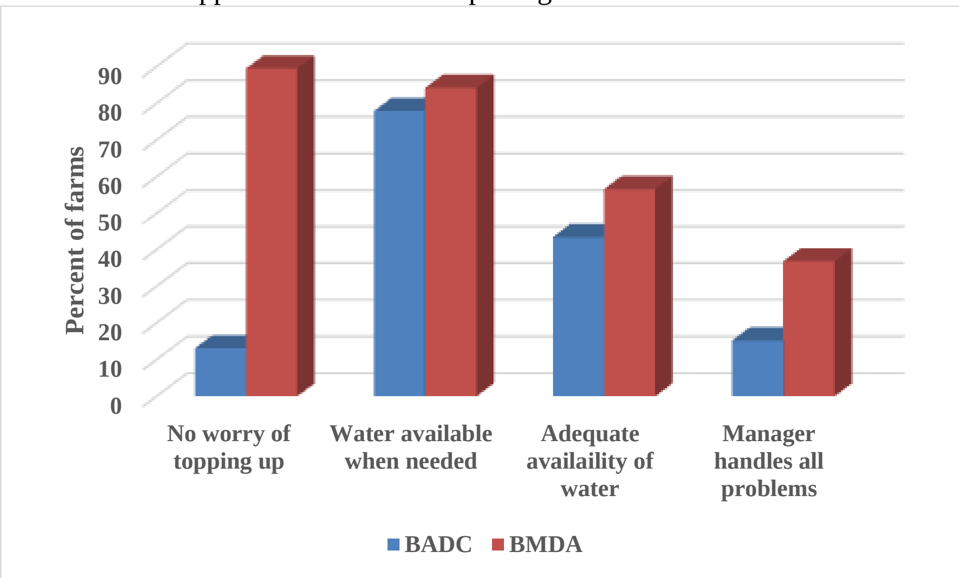


**Fig. 8: Advantages of manager controlled smart card with volumetric pricing**

*Pricing of water by area* is the norm in case of all privately owned irrigation particularly STWs but we find this practice also in case of BMDA and BADC and more so for the latter. As farmers opine, the great advantage, not unsurprisingly, is the simplicity of the method. “I pay you certain amount of money by per unit of area for the whole season and the you supply the water, come what may.” The replies of advantages indicate clearly that the saving the trouble of regular field checking is a major issue and so is the ease of payment which interesting though high for all systems, not so much for private DTWs (Fig. 9). In fact, in case of private DTWs, there seems to be a concern regarding ease of water charge payments which ties with comparatively low percentage of lack of worry regarding water availability in these cases.

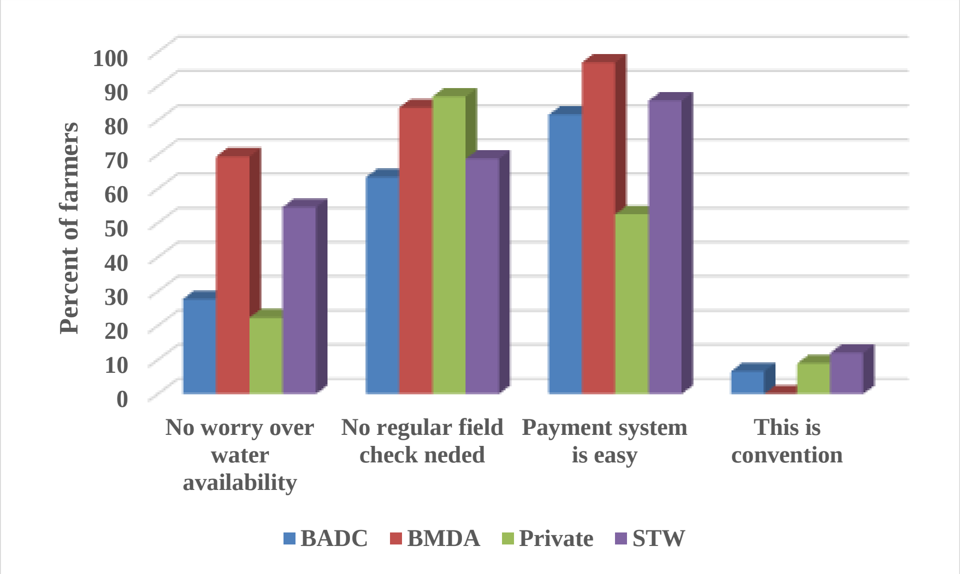


**Fig. 9: Advantages of water pricing by area**

High cost appears to be a major *disadvantage of water pricing by area* (Fig. 10). Interestingly BMDA farmers are less sensitive about cost than others such as BADC, private DTWs and STW farmers. But all are roughly equally concerned about having no control over the supply of water, particularly its timing which is important in boro cultivation. Lack of control appears to be a major issue mainly in case of BMDA farmers.

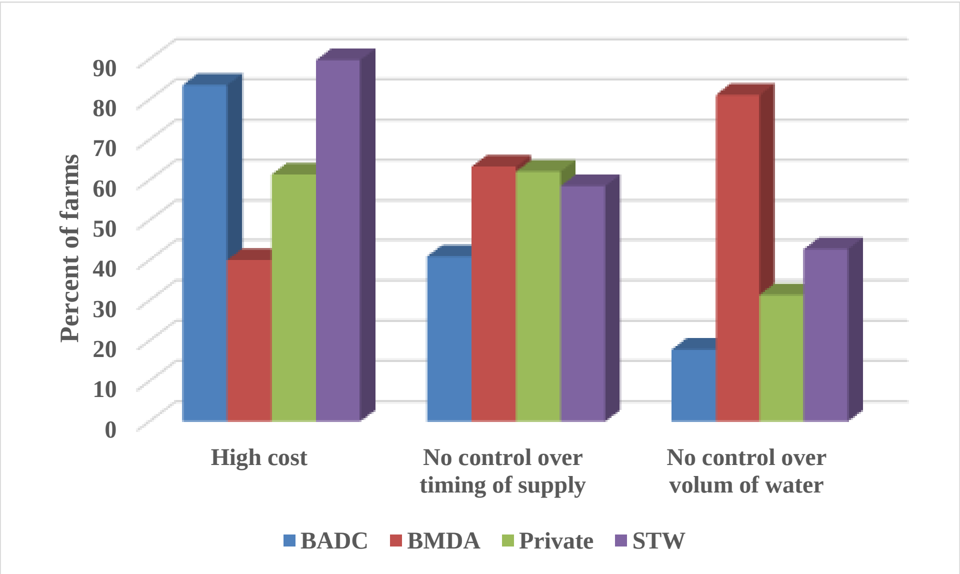


**Fig. 10: Disadvantages of water pricing by area**

Whether the control is with the farmer due to own smart card, or with the manager due to the card being held by him, the actual payment may be in either cash or kind. For BADC, we find that 71% farmers pay in cash while 25% pay in kind. For BMDA, own smart card means that it is paid in cash. But as we find there are also manager controlled DTWs under BMDA and while nothing is stated whether this is in kind or in cash, we take it to be in cash. For private DTWs and STWs, cash is the primary means of payment, 84% for the former and 80% for the latter. In kind payment account for 15% and 20% respectively.

*3.8.9 Water management practices*

The above findings, particularly availability of water in time and in adequate amount relates to the water using practices of farmers. The age-old method is to keep the rice field flooded. However, this method seems to be less practiced now. Only 20 to 34% of farmers practice flooded rice field method. There seems to be two major overriding concerns for practicing flooded rice agriculture.

These are saving on weeding and related labour costs (64 to 81 percent) and ensuring yield (66-85%). However, farmers are also aware of the disadvantages of flooded rice agriculture.
The disadvantages relate to basically three types of issues. These are "too much water may applied" (49-69%), "irrigation costs may be high" (54-87%) and "yield of crop is not ensured" (9-32%).

*Knowledge about AWD*

Lowering water use and saving on costs and at the same time not compromising on yield appears to be the hall mark of AWD. We have tried to find out as to how far farmers are knowledgeable about AWD. As we find, very few farmers know about this. The maximum is 5.7% under BMDA. As the knowledge about AWD is for all practical purposes missing, we have not analysed the few farmers who had some knowledge about it or its practice or advantages and disadvantages.

*Block irrigation*

Block irrigation allows farmers to be involved on a community basis with neighbouring farmers to better manage water supply across a group of farmers. We find that very few farmers under BMDA practice block irrigation while among BADC farmers, the percentage is somewhat substantial at 40%. Similar is the case with private DTW farmers (39%). For STW farmers it is 13%.

Ease of collective management is the overriding concern as 72% of BADC, 60% of BMDA, around 97% of private DTW and STW farmers state. The next in importance is lowering of irrigation costs – for BADC : 72%, BMDA: 60%, private DTW: 20% and STW: 78%.

The advantages may be outweighed by certain disadvantages. These include problem of cultivating different crops as without the same crop or variety of crop being cultivated, it is difficult to otherwise manage water as different crops need water in different quantities and timing. For example, for non-rice crops, up to 84% of farms particularly for private DTW think this is difficult. On the other hand, many do think that without farmers' association such block irrigation may not be feasible.

*3.8.10 Other practices that may save water and reduce costs*

Several other practices may save water for irrigation and lower costs either by lowering water charges (in case where volumetric pricing is used) or saving other costs. *Dry seeding of rice* is one such technology. When asked about this practice, only 1.3 percent farmers was found to have some knowledge of it. Among those who did, BADC farmers topped the list (although the total number was just 19).

Among them however, they saw the advantage in terms of mainly in terms of some water saving and reducing cultivation (i.e., ploughing) costs. The few BMDA farmers who knew about it also saw the advantage in terms of water saving.

Comparatively more farmers (nearly 13%, varying from 9 to 19%)) have practiced *ploughing of field after harvesting.* The advantages they see mainly in terms of preserving "zoe" and reducing weeds and pests which save costs of labour and pesticides (Fig. 11). Note however, that other advantages such as saving primary tillage costs of next crops as well as preserving and availability of soil nutrients are not insubstantial either.

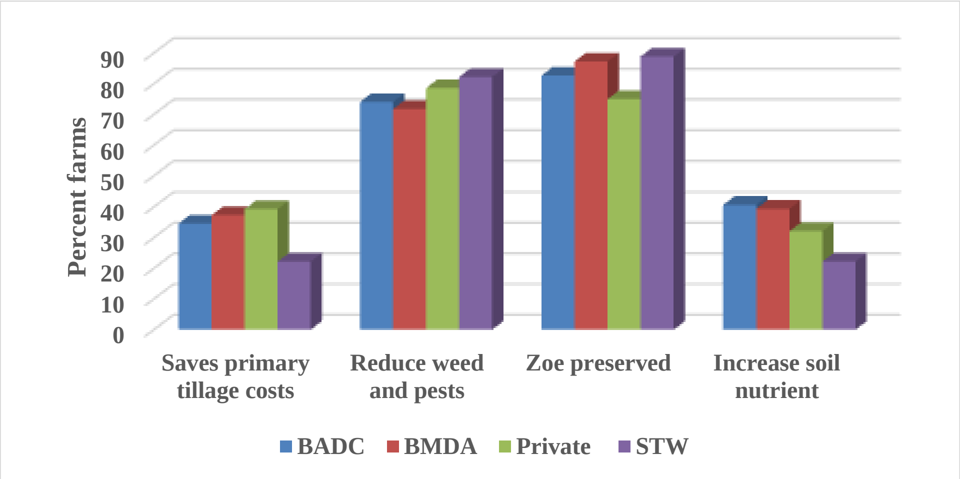


**Fig. 11: Advantages of ploughing field after harvest**

There are contrary views also in terms of reducing primary tillage costs. On the other hand, most other think that such practice is not suitable in all conditions.

3.8.11 Water quality problems

How good is the water quality supplied under the DTWs and STWs. As complained by the farmers, water quality problems exist in case of private DTWs (64.8%), followed by BADC DTWs (43.3%). STWs clients complain about water quality in about 30% cases. For BMDA, the problem apparently is rare as only 5.8% pointed out the problem.

Problem of iron in water is what most of them complained about. Practically all who responded to the question pointed to this problem. The problem of arsenic was also pointed out but by very few, an average of 10% of those who responded.

*3.8.12 Irrigation water distribution system*

Water from the pump to the farmers field may be through several systems. It may be over earthen channels which lead to percolation and evaporation loss which is known to be substantial. To remedy this, the general remedy is to put in buried pipes from the pump to a riser near the farmers' filed from where it may be again carried through earthen or pucca channels or farmers may use hose pipes to reduce the loss of water. The survey tried to find out the main practices by main irrigation management systems. What we find is shown in Fig. 12.

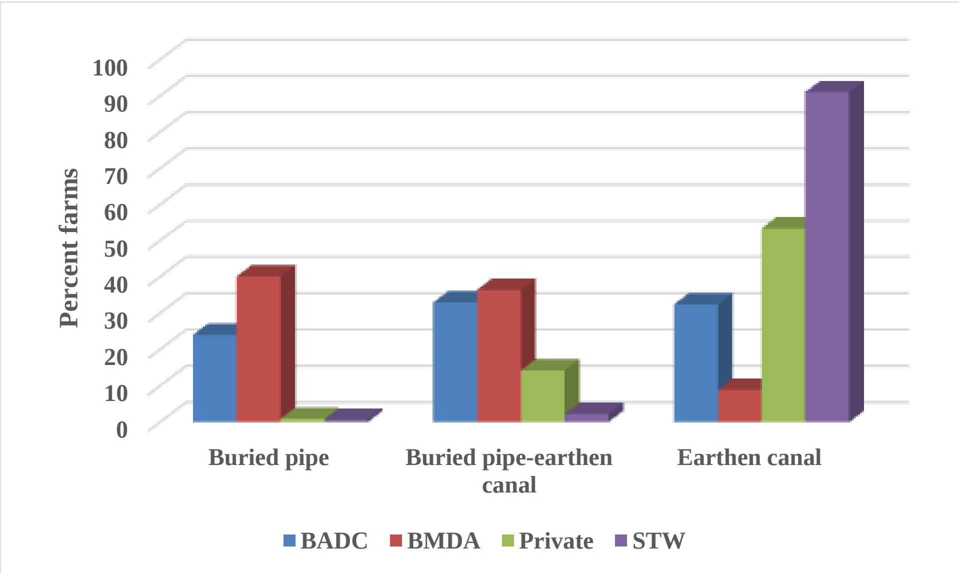


**Fig. 12: Irrigation water supply infrastructure**

We find major differences between irrigation management systems in terms of the irrigation infrastructure. Buried pipes alone or with earthen canals are used in BMDA and BADC DTW systems. In contrast, these are rare or non-existent in case of privately owned DTWs or STW for the obvious reason that the water sellers' responsibility is to simply supply water. In case of private DTWs, the seller may put in some buried pipe to lower his lifting of water to supply the same water to the buyers. In case of STWs, because of the small area involved, it is not in interest of the water seller to make additional investment for buried pipes. Instead they depend overwhelmingly on earthen canals which of course lead to water losses. This is an area which may need more thorough examination for intervention in case of private water suppliers.

*3.8.13 Water users' association issues*

Many of the issues related to water use, particularly when new technologies are introduced may be facilitated if there are effective water users' association. This helps in learning from each other and also taking collective decisions when community-based or neighbouring farms need to take such decisions and implement them. For example, constructing channels for supplying water to the fields need farmers who might be affected to come to an agreement regarding sharing the costs or about the layout of the channels.

Table 2 shows the information related to water users' association by irrigation management groups. These indicate that such associations are absent in case of STWs but up to 30% or so cases in case of BADC, BMDA and private DTWs/ Respondents were members in most case but less so in case of private DTWs and STWs. The associations had been in operation at least for 4-6 years where these exist. And apparently the associations are active as meetings are held regularly, as opined by 97% farmers under BADC, 85 cases in BMDA and 76 percent cases for private DTWs. And farmers do think that these are beneficial.

**Table 2: Water Users Association related information**
(Percent of farmers responding)

| Indicators | BADC | BMDA | Private DTW | STW |
|---|---|---|---|---|
| WUA exists | 23.1 | 31.4 | 28.4 | 0.6 |
| Membership by respondent | 89.7 | 93.8 | 64.1 | 33.3 |
| Av. Membership (N) | 47 | 128 | 17 | 25 |
| Existing years (at least) | 6 | 4 | 5 | 4 |
| If meetings held regularly (yes) | 95 | 81 | 66 | - |
| Any benefit received | 97 | 85 | 76 | - |

Irrigation management to lower its cost and conserve water necessitates not simply technology but also community involvement as otherwise there may be a free rider problem. If managers control cards, or payment is by area, the particular water buyer may not bother about the volume of water applied. That means that the person with own smart card may be saving water but the former farmer simply has a free ride on him. Unless the community as a whole resists such practices, water saving and conservation is unlikely to be possible. Volumetric pricing is a necessary condition but may not be sufficient to innovate for better water using technology (such as AWD). Community involvement will also have to be there. This si also necessary for putting in infrastructures such as buried pipes which automatically conserves water

For STWs, and also for private DTWs this is going to be another story. We expect to soon come up with pilot ideas regarding how water conservation in practice may be done in such cases.

### 3.9 Costs of production: Irrigation and other costs

The previous section has discussed in detail the various water management practices, norms and interventions either on an individual far or on a community basis. All such practices have implications for costs of irrigation and other associated costs as well as yield and benefits out of the cropping activities of the farmers. In this section we try to go into details of these issues. First the actual cropping pattern.

#### *3.9.1 Crops cultivated*

Our focus is on irrigation management and naturally, as boro season crops are the main irrigated ones, we tried to find out what crops the farmers grow. The information provided by farmers show decisively that it is HYV boro eother alone or in association with other crops that hold sway above all. This is shown clearly in Fig. 13.

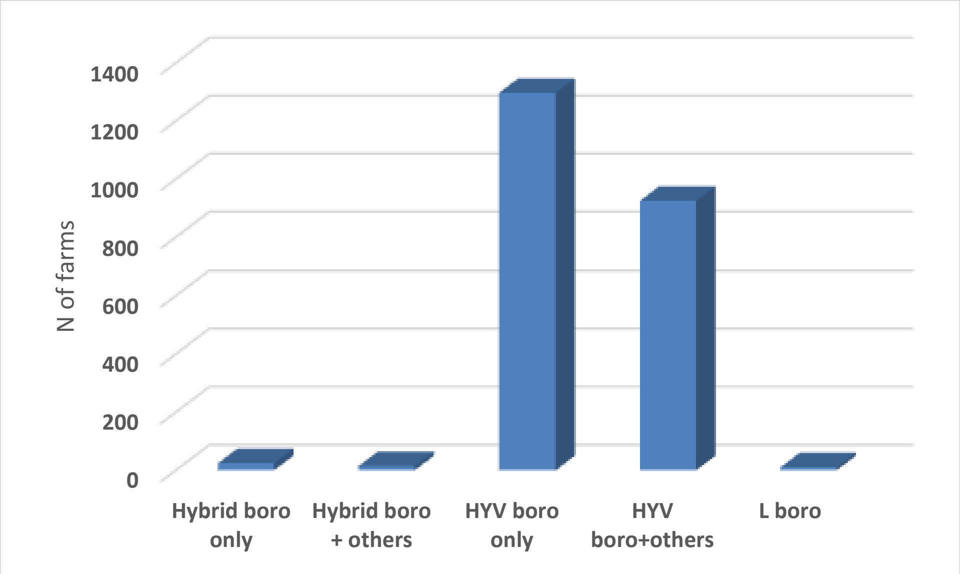


**Fig. 13: Crops cultivated by farmers during boro season**

Fig. 13 shows that farmers mostly cultivate either HYV boro alone or HYV boro and other crops. Hybrid boro is comparatively far rare. Local boro is more so. Non-rice crops alone are rarer still.

However, on probing further, we find an interesting variation across irrigation equipment ownership which also mean somewhat different management practices including pricing as discussed earlier. The results disaggregating irrigation equipment ownership, we find that while BADC, private DTWs and STW farmers show behaviour similar to the general picture indicated above, BMDA farmers seem to be a group apart. Fig. 14 shows this vividly.

The figure indicates that while HYB boro alone is the dominant crop in all cases, its significance is far less in case of BMDA farmers compared to others. However, this does not mean that BMDA farmers do not cultivate HYV boro as much as others. They appear to mix other crops along with HYV boro. In fact, STW farmers also appear to indicate similar behaviour of crop diversification. Could it be the pricing system, better control over water application or what?

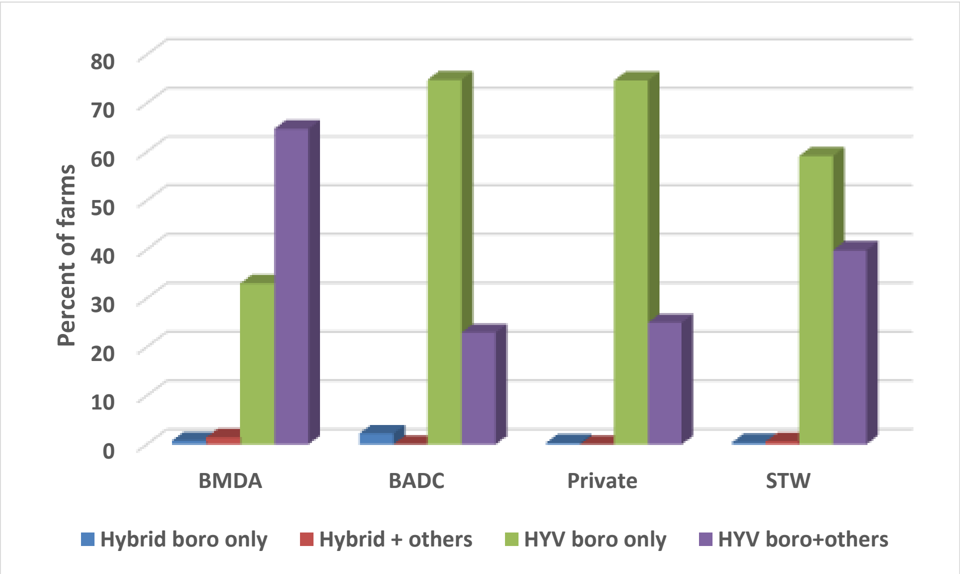


**Fig. 14**

**Crop cultivation during boro season by irrigation equipment ownership**

*3.9.2 Land levels*

Which crops to be grown in any given season depends among others on the level of land as well as water availability. Here we first try to give some impression based on farmers' ideas of the level of their land. Of course, this idea may vary by area characteristics, what may be high in some areas, may not be so in others. Given this caveat, we find that the average area under high, medium and low land do vary quite significantly across the irrigation management practices. Fig. 15 provides the relevant information.

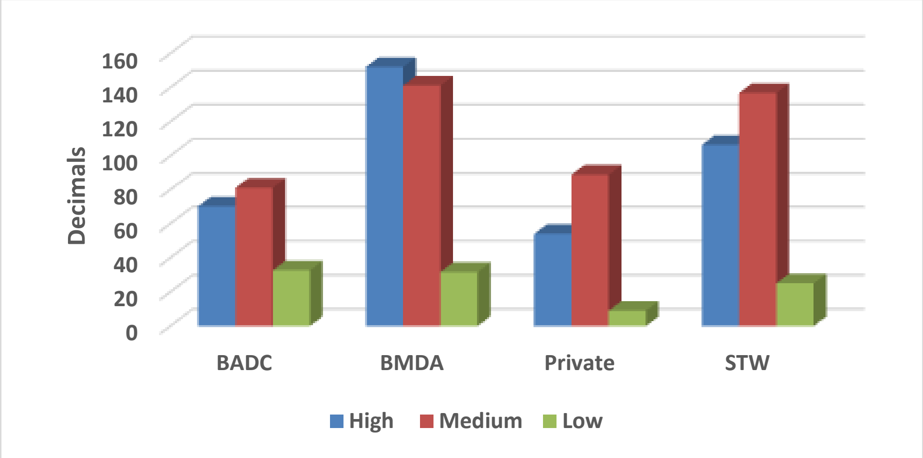


**Fig. 15: Average area of land levels by DTW and STW areas**

We find that the average highland appears to be most prevalent, not surprisingly, in BMDA areas, but also under STW farmers. Similarly medium level land is much larger in area in both BMDA and STW areas. In comparison, for both BADC and private DTW areas, high and medium lands are much lower. Low land is much less in all types of areas.

*3.9.3 Crops grown and irrigation availability*

We have found that local boro is almost absent during the boro season. It is HYV boro which is the most preferred crop and this cannot be grown properly without good availability of irrigation water. Indeed, we find that whether under owned and self-cultivated land or land taken in under various arrangements (shared/rented/mortgaged in) the area under HYV boro is synonymous with area under irrigation (Fig. 16). However, we again find that the areas under BMDA are the largest while those under private DTW areas are the smallest. BADC DTW and STW areas appear to have similar size and distribution of owned-self cultivated and taken in land.

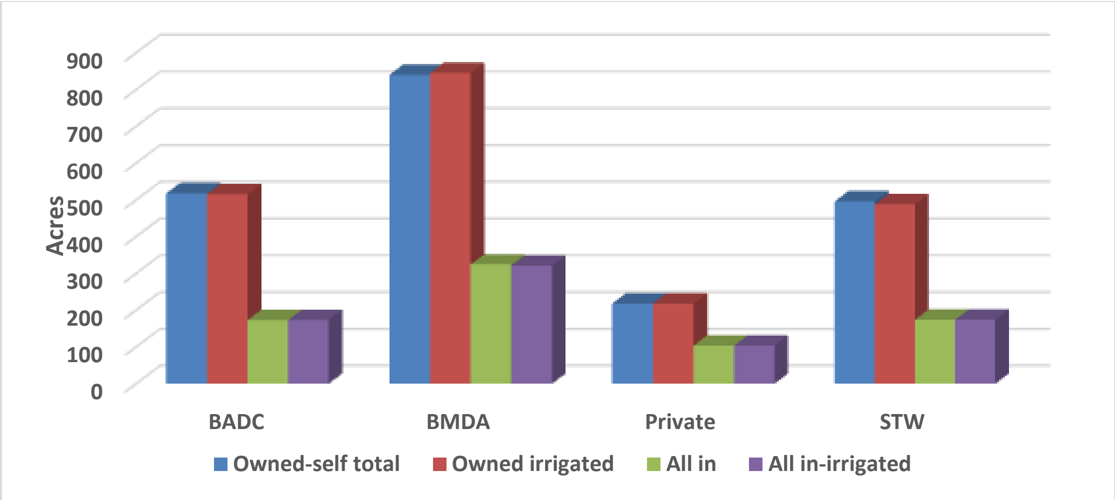


**Fig. 16**

**Owned-self cultivated and all taken in land area and irrigation availability**

### *3.9.4 Yield rates of HYV boro*

Yield rates depend on many factors including inputs application, their timeliness etc s well as tenurial arrangements. Usually one expects lower yields on tenured land. The arguments are well-known. Without getting into these details, we find that generally the hypothesis is true in all cases. As Fig. 17 shows, the yield rates are not only lower, in some cases, these seem to be almost as half of that under owned and self-cultivated land. We also find that the yield rates of BMDA owned land appear to be the highest among all while BADC and private DTW farmers appear to be on the lower side.

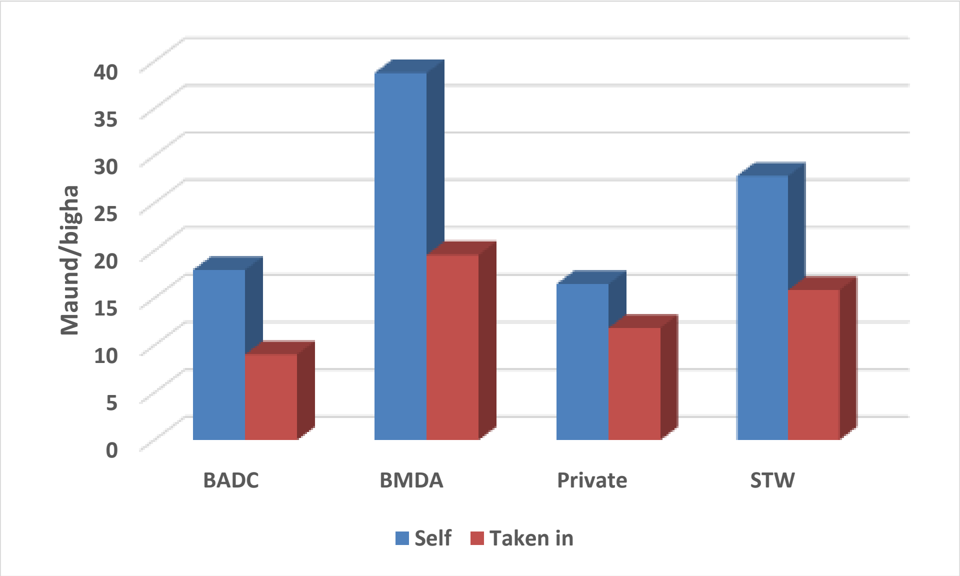


**Fig. 17: Yield rates of HYV boro by tenurial arrangement**
(maunds/bigha)

# EFFECTS OF FLOATING AGRICULTURE PRACTICE ON THE WATER BODY OF POND

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## Abstract

This experiment was conducted at RARS, Rahmatpur, Barishal to determine the change of water quality of ponds for cultivating fish and household uses. The water samples were collected from three selected ponds of RARS, Rahmatpur, Barishal. The selected ponds were mentioned as; FL-1 (Floating Agriculture practiced since 2015), FL-2 (Floating Agriculture practiced since 2018) and F (Fresh Pond). The water quality parameters were analyzed from TCL and Soil Lab, BRAC, Gazipur. It was not possible to collect water samples in some months of 2020 and 2021 due to the lockdown retained for Covid-19 pandemic. The water temperature was observed below $34^0$C which is good for fish cultivation during the study period at all three ponds. The pH level was ranged from 6.66-8.59 at all three selected ponds. The (UIA) Un Ionized Ammonia level at all selected ponds were suitable for only channel catfish production. However, the application of fertilizers and pesticides effected the UIA level. The total dissolved solids (TDS) were in desirable limit but in case of floating agriculture practiced ponds (FL-1 and FL-2) the TDS level was found much higher than fresh pond (F). The Ca levels were in affordable range for only channel fish cultivation. The P values were found good for fish production but the floating agriculture practiced ponds have higher P levels than fresh pond. According to the observation, the nitrate levels during the study age were in tolerable limit. No detrimental effects of floating agriculture were detected in using the enclosed ponds water for household uses.

## Introduction

The southern part of the country consists of coastal lowland and mangrove areas formed by the delta of large river systems. Bangladesh suffers from flooding almost every year to a small or large extent, and in the case of the years with small-scale flooding, the losses have not been assessed properly, but for those years with large-scale flooding, different institutes try to assess the loss from their perspective (Mirza and Ahmad 2005). In some parts of Bangladesh, most affected by flood and where water remains for a prolonged period. farmers are using their submerged lands for crop production by adopting traditional methods which are similar to hydroponic agriculture practices, i.e. floating agriculture, whereby plants can be grown on the water in a bio-land or floating bed of water hyacinth, algae or other plant residues. The procedure of making the floating bed is usually the same, however the size, shape and local materials vary from region to region (Islam and Atkins 2007; APEIS 2004).

The most commonly used material is water hyacinth, but topapana, son ghash, nollghash, wood ash, and dissected coconut fibers are also used (Islam and Atkins 2007: 131). Water hyacinth is utilized not only for the foundation of production system as floating beds during the monsoon season but also for compost especially during the winter cultivation on the ground. Because crops could absorb prime nutrients such as nitrogen, potassium and phosphorus from the floating beds and below water, there is almost no need for fertilizer input. This technique brings many ecological benefits, such as the good use of an invasive species like water hyacinth – a very effective way to control this notorious weed; platform residues can be used as organic fertilizer (this practice cuts pollution from chemical fertilizers). The water quality of the canals and ponds used for floating cultivation were going down day by day for decomposition of water hyacinth, topapana, son ghash, nollghash, wood ash and coconut fiber in large scale. So it is needed to analyze the water quality of that canals and ponds for fish cultivation and household use. Objective of the experiment were given below

i) To determine the change of water quality of ponds for cultivating fish and household uses.

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[2] *CSO (in-charge), IWM Division, BARI, Gazipur*
[3] *SSO, IWM Division, BARI, Gazipur*
[4] *PSO, RARS, BARI, Rahmatpur, Barishal*

## Materials and Methods

The experimental water samples were collected from Regional Agricultural Research Station, Rahmatpur, Barishal. Three water samples were collected from three selected ponds of Regional Agricultural Research Station, Rahmatpur, Barishal. The two samples were collected from floating agriculture practice ponds and one sample was collected from a fresh pond. The treatments of the experiment were given below:

FL-1 = Floating Agriculture Practice as well as fish culture since 2015

FL-2 = Floating Agriculture Practice as well as fish culture since 2018

F = Fresh Pond

The water quality parameters of the collected samples were analyzed at TLC and soil lab of BARDC, Gazipur. The water quality parameters were given below

| | | | | |
|---|---|---|---|---|
| 1. Temperature | 2. pH | 3. Ammonium ($NH_4$) | 4. Nitrate ($No_3$) | 5. TDS |
| 6. Calcium (Ca) | 7. Phosphorus (P) | 8. Nitrogen (N) | 9.DO | |

## Results and Discussion

Fish do not like any kind of changes in their environment. Anita Bhatnagar and Pooja Devi (2013) stated that any changes add stress to the fish and the larger and faster the changes, the greater the stress. So the maintenance of all the factors becomes very essential for getting maximum yield in a fish pond. Adequate oxygen, proper temperature, transparency, limited levels of metabolites and other environmental factors affecting fish culture characterize good water quality. The initial studies of water quality of a fish pond in India were probably conducted by Sewell (1927) and Pruthi (1932). After that many workers have studied the physico-chemical condition of inland waters either in relation to fish mortality or as part of general hydrological survey (Alikunhi *et al*., 1952: Upadhyaya, 1964). Workers (Mumtazuddin et al., 1982: Delince, 1992: Garg and Bhatnagar, 1999: Bhatnagar, 2008) also have studied the details of various pond ecosystems. Bhatnagar and Singh (2010) studied the pond fish culture in relation to water quality in Haryana. However, this experiment would provide the basic guidelines, parameter wise for the fish farmers who are interested in floating agriculture practice as well as fish culture in a single pond via maintaining water quality of their ponds.

Temperature is defined as the degree of hotness or coldness in the body of a living organism either in water or on land (Lucinda and Martin, 1999). As fish is a cold blooded animal, its body temperature changes according to that of environment affecting its metabolism and physiology and ultimately affecting the production. Higher temperature increases the rate of bio-chemical activity of the micro biota, plant respiratory rate, and so increase in oxygen demand. It further cause decreased solubility of oxygen and also increased level of ammonia in water. According to Delince (1992) 30-$35^0$ C is tolerable to fish. Bhatnagar *et al.* (2004) suggested that the levels of temperature as 28-$32^0$C good for tropical major carps, 25-$30^0$C – ideal for *Penaeous monodon* culture; < $20^0$C – sub lethal for growth and survival for fishes; <$12^0$C – lethal but good for cold water species and > $35^0$C- lethal to maximum number of fish species. According to Santhosh and Singh (2007) suitable water temperature for carp culture is between 24 and $30^0$C. Rendering to Figure 1 the average temperature was found within $26.70^0$C to $33.60^0$C at all the selected ponds during last three years. it could be stated that the temperature of all selected ponds was found suitable for fish cultivation.

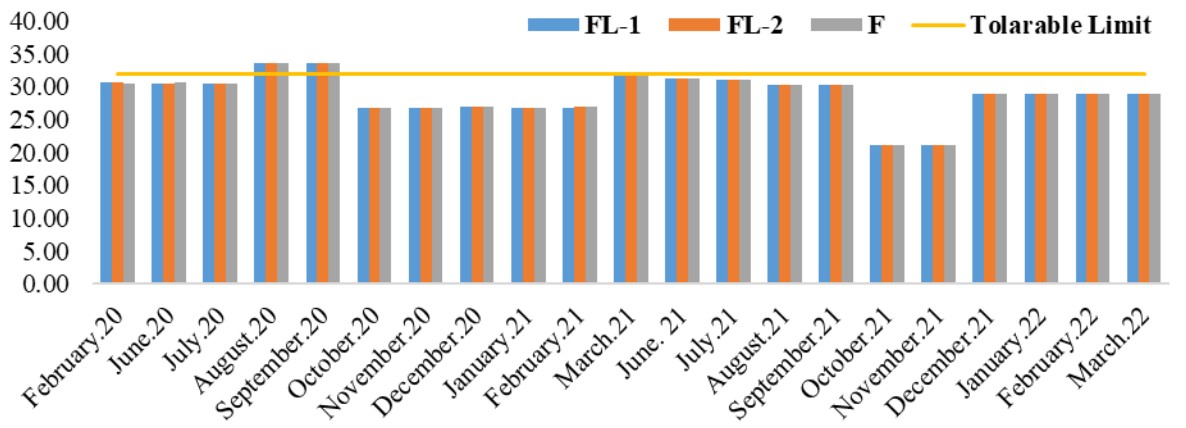


**Figure 1. Month wise Temperature (0C) values of different ponds.**

pH is measured mathematically by, the negative logarithm of hydrogen ions concentration. The pH of natural water is greatly influenced by the concentration of carbon dioxide which is an acidic gas (Boyd, 1979). Fish have an average blood pH of 7.4, a little deviation from this value, generally between 7.0 to 8.5 is more optimum and conducive to fish life. pH between 7 to 8.5 is ideal for biological productivity, fishes can become stressed in water with a pH ranging from 4.0 to 6.5 and 9.0 to 11.0 and death is almost certain at a pH of less than 4.0 or greater than 11.0 (Ekubo and Abowei, 2011). According to Santhosh and Singh (2007) the suitable pH range for fish culture is between 6.7 and 9.5 and ideal pH level is between 7.5 and 8.5 and above and below this is stressful to the fishes. Ideally, an aquaculture pond should have a pH between 6.5 and 9 (Wurts and Durborow, 1992: Bhatnagar *et al*., 2004). From figure 2, it could be stated that the pH range was within the limit of 6.5 to 9 in all ponds. A pH value higher than 8.5 indicates that a significant amount of sodium bicarbonate may be present in the water. So pH level higher than 8.5 and lower than 5 is harmful for household uses.

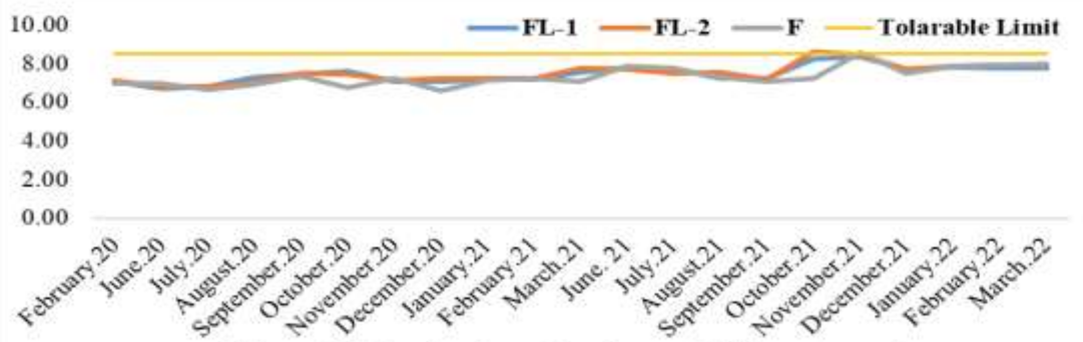


**Figure 2. Month wise pH values of different ponds.**

Animals produce ammonia as a byproduct of protein metabolism. What is measured by chemical analysis (Nessler method) for ammonia is called total ammonia nitrogen (TAN) because it includes two forms of ammonia: ammonia ($NH_3$), the unionized form, and the ammonium ion ($NH_4^+$). The unionized ammonia (UIA) is toxic to fish. The temperature and pH of water affects the ratio of ($NH_4^+$):($NH_3$) in water. For salmonid fishes, it is recommended that the concentration of UIA not exceed 0.0125 to 0.02 mg/L to maintain health of the fish, however, the toxic concentrations of UIA ($NH_3$) for trout are about 0.32 mg/L for rainbow trout, but 1.50-3.10 for channel catfish (Ruffier et al. 1981, cited by Boyd 1990a). Thus, a UIA of 1.7 mg/L, would be an expected to cause mortality of most fish, and it would be stressful for channel catfish. From figure 3 it was observed that the unionized ammonia level is suitable for channel catfish but not suitable for salmonid and craps in some cases. Bhatnagar *et al*. (2004) suggested 0.01-0.5 ppm is desirable for shrimp; >0.4 ppm is lethal to many fishes & prawn species; 0.05-0.4 ppm has sublethal effect and <0.05 ppm is safe for many tropical fish species and prawns. Bhatnagar and Singh (2010) recommended the level of ammonia (<0.2 mg L-1) suitable for pond fishery.

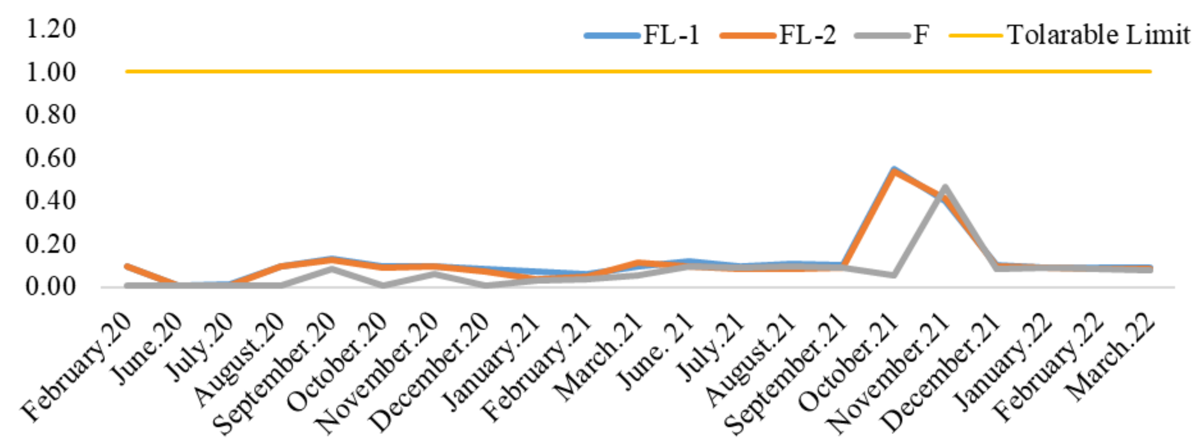


**Figure 3. Month wise UIA (PPM) values of different ponds.**

The *total dissolved solids*, or *TDS*, includes ionized and non ionized matter but only the former is reflected in the conductivity. Where TDS are high the water may be "saline" and the applicable parameter "Salinity". Salinity is defined as the total concentration of electrically charged ions (cations – Ca++, Mg++, K+, Na+ ; anions – CO3-, HCO3-, SO4-, Cl- and other components such as NO3-, NH4+ and PO4-). Salinity is a major driving factor that affects the density and growth of aquatic organism's population (Jamabo, 2008). Garg and Bhatnagar (1996) have given desirable range 2 ppt for common carp; however, Bhatnagar *et al*. (2004) gave different ideal levels of salinity as 10-20 ppt for *P. monodon*; 10-25 ppt for euryhaline species and 25-28 ppt for *P. indicus*. Barman *et al*. (2005) gave a level of 10 ppt suitable for *Mugil cephalus* and Garg *et al*. (2003) suggested 25 ppt for *Chanos chanos* (Forsskal). From figure 4, it was observed that the total dissolved solids were in desirable limit but in case of floating agriculture practiced ponds the TDS was found more than fresh pond. Values of less than 500 ppm (mg/L) are satisfactory and up to 1,000 ppm (mg/L) could be tolerated with little effect in household uses.

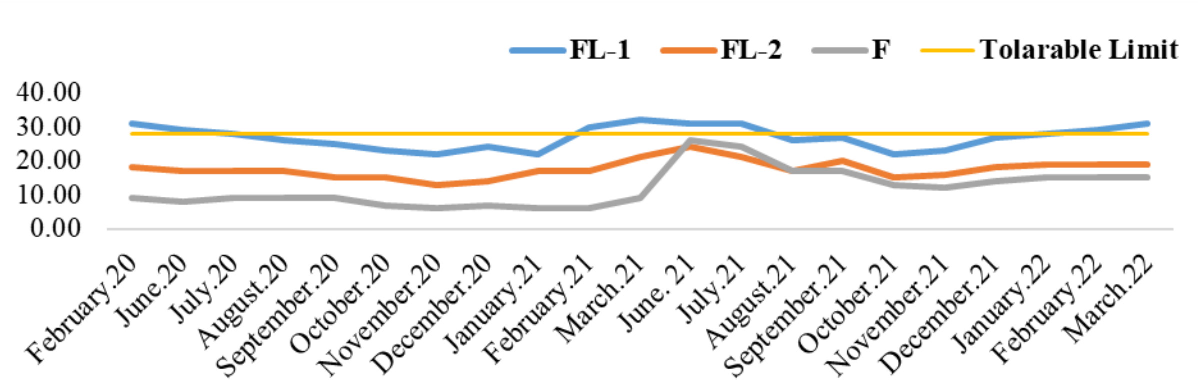


**Figure 4. Month wise TDS (PPM) values of different ponds.**

Calcium is generally present in soil as carbonate and most important environmental, divalent salt in fish culture water. Fish can absorb calcium either from the water or from food. Wurts and Durborow (1992) recommended range for free calcium in culture waters is 25 to 100 ppm (63 to 250 ppm $CaCO_3$ hardness) and according to them Channel catfish can tolerate minimum level of mineral calcium in their feed but may grow slowly under such conditions. According to figure 5, the Ca values were in affordable range for all kinds of fish cultivation.

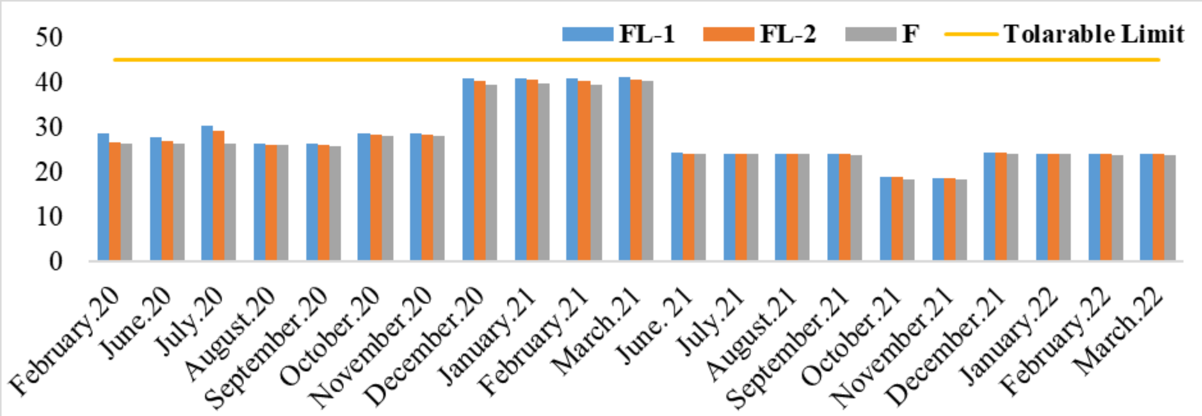

**Figure 5. Month wise Ca (PPM) values of different ponds.**

Almost all of the phosphorus (P) present in water is in the form of phosphate (PO4) and in surface water mainly present as bound to living or dead particulate matter and in the soil is found as insoluble Ca3(P04)2 and adsorbed phosphates on colloids except under highly acid conditions. It is an essential plant nutrient as it is often in limited supply and stimulates plant (algae) growth and its role for increasing the aquatic productivity is well recognized. According to Stone and Thomforde (2004) the phosphate level of 0.06 ppm is desirable for fish culture. Bhatnagar *et al*. (2004) suggested 0.05-0.07 ppm is optimum and productive; 1.0 ppm is good for plankton/shrimp production. From figure 6 it was observed that the P values were good for plankton/shrimp production but were above limit for other fish production.

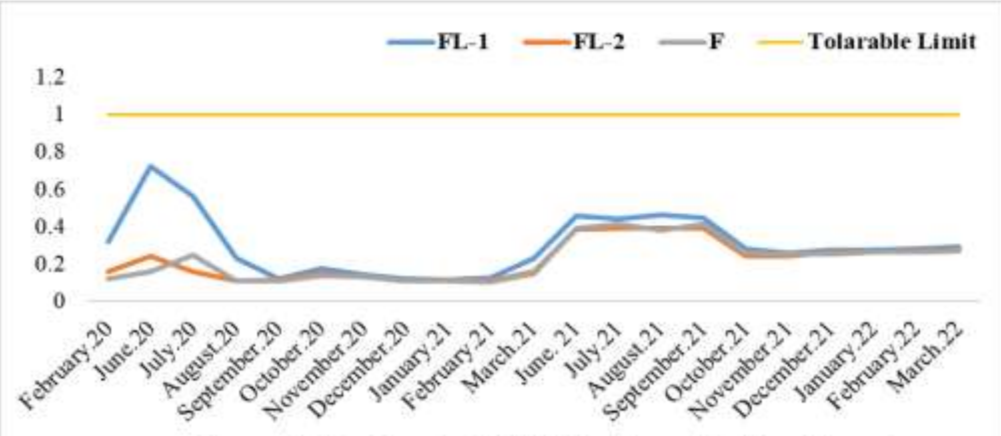

**Figure 6. Month wise P (PPM) values of different ponds.**

Where ammonia and nitrite were toxic to the fish, Nitrate is harmless and is produced by the autotrophic *Nitrobacter* bacteria combining oxygen and nitrite. Nitrate levels are normally stabilized in the 50-100 ppm range. According to Stone and Thomforde (2004) nitrate is relatively nontoxic to fish and not cause any health hazard except at exceedingly high levels (above 90 ppm). However, OATA (2008) recommends that nitrate levels in marine systems never exceed 100 ppm. According to figure 7, it was observed that the nitrate values in the all months were in tolerable limit. Nitrate in excess of 45 mg/L (or in excess of 10 mg/L if reported as nitrate-nitrogen) is of health significance to pregnant women and infants under six months.

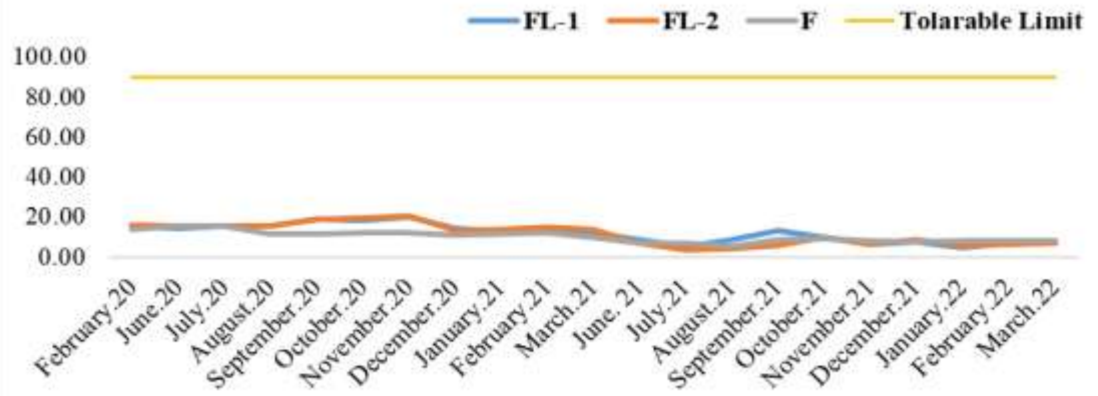


**Figure 7. Month wise $NO_3$ (PPM) values of different ponds.**

Oxygen is the first limiting factor for growth and well-being of fish. Fish require oxygen for respiration, which physiologists express as mg of oxygen consumed per kilogram of fish per hour (mgO2/kg/h). The respiratory rate increases with increasing temperature, activity, and following feeding, but decreases with increasing mean weight. In ponds, the major source of oxygen is from algal photosynthesis and from wind mixing the air and water. *Robert C. Summerfelt* stated that at temperatures optimum for growth, fish are stressed at oxygen concentrations less than 5 mg/L. If the condition is chronic, fish stop feeding, growth slows down, stress-related disease begins. For rainbow trout, mortality may begin at 3 mg/L, but channel catfish tolerate less than 2 mg/L before mortality commences. However, if the gills of fish are damaged by parasites (hamburger gill disease is a good example of a severe protozoan disease of the gills of channel catfish), the fish may die when oxygen concentrations drop only slightly below 5 mg/L. From figure 8, it could be stated that the DO levels of all three selected ponds were suitable for all kinds of fish culture. According to Bhatnagar and Singh (2010) and Bhatnagar *et al*. (2004) DO level >5ppm is essential to support good fish production.

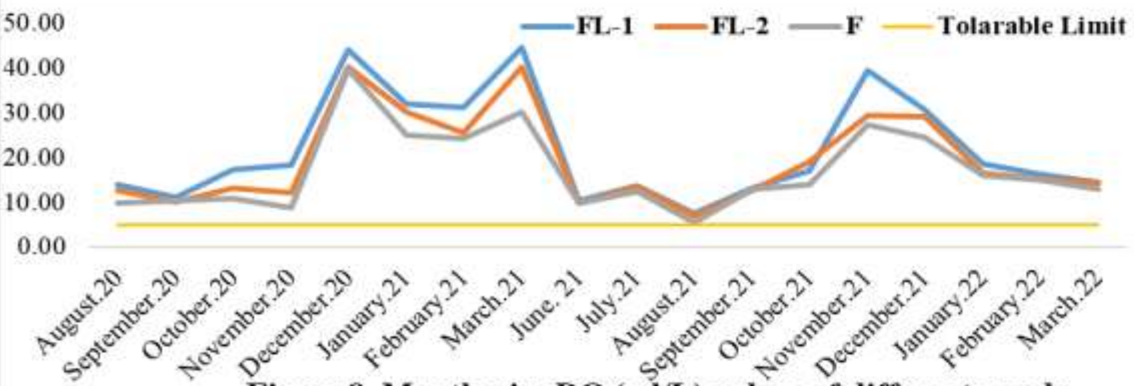


**Figure 8. Month wise DO (ml/L) values of different ponds.**

## Conclusion

The experiment was conducted during last three years to perceive the effect of floating agriculture practice on the water quality of the ponds of RARS, Rahmatpur, Barishal. All parameters of water were still suitable for fish cultivation but due to floating agriculture practiced in an enclosed environment, the water quality became effected for fish cultivation to some extent owing to the application of fertilizers and pesticides. So bio-fertilizers and bio-pesticides were the solution to protect water quality for fish cultivation. The floating agriculture practice do not have any harmful effect on using the pond water in household uses.

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## *PROJECT (SACP-IWM PART):*

# DISSEMINATION OF WATER SAVING TECHNOLOGIES FOR NON-RICE CROPS IN SALINE PRONE AREAS OF BANGLADESH

M.A. HOSSAIN[1], D.K. ROY[2], S.K. BISWAS[2], K.F.I. MURAD[3], S.S.A. KAMAR[3]

## Abstract

Demonstrations of solar powered water saving irrigation technologies on crop production were executed at five upazillas under five districts. In 2019-2020, demonstrations were conducted at three upazilas under three districts of the southern saline prone areas of Bangladesh. In 2020-2021, field demonstrations were extended to two more upazillas in the districts of Bhola and Noakhali. Again in 2021-2022, field demonstrations were continued to five upazillas under five districts of southern Bangladesh. In 2019-2020, twelve demonstrations were conducted at the selected areas whereas in 2020-2021, four additional demonstrations were performed and in 2021-2022 fifteen demonstrations were conducted at the selected locations. Two water saving irrigation technologies (AFI and drip irrigation) were compared with the traditional farmer practice. Alternet furrow irrigation (AFI) was used for maize and sunflower cultivation and drip irrigation system was used for tomato, brinjal, sweetgourd and watermelon cultivation. Solar power was also used for mitigating the pumping cost in drip irrigation system. In general, the AFI technology showed superior performance over the traditional farmers' practices for maize and sunflower cultivation in the study areas for both growing seasons of 2019-2020 and 2020-2021. This higher performance was evidenced by the better numeric values of the yield and yield attributing characters of both sunflower and maize crops in AFI adopted plots when compared to the traditional irrigation practice used by the farmers in the study areas. Likewise, sstatistically significant yield difference was observed among the treatments (solar powered drip irrigation system and farmer's practice) for sweet gourd, brinjal, watermelon and tomato cultivation in the study areas in 2019-2020, 2020-2021 and 2021-2022 growing seasons. AFI and solar powered drip irrigation treatments provided highest BCR for all crops and for the consecutive three growing seasons. The farmers were benefited and interested in using this promising water saving irrigation technologies.

## Introduction

Bangladesh is an agro-based country where agriculture has enormous contribution to the national economy and to livelihood of the people (Murshed-E-Jahan and Pemsl, 2011). Agricultural growth of Bangladesh has accelerated after independence, where irrigation expansion happened during mid 80's (Hoque, 2001). But the agricultural growth has been impeded due to natural disasters and fluctuations in food prices. This natural disaster mainly occurs due to unfavorable weather which is now severe (Harun-ur-Rashid and Islam, 2007). Salinity and drought are the main stress environments in Bangladesh (Athar and Ashraf, 2009; Harun-ur-Rashid and Islam, 2007). The nature and extent of these environments vary with season, topography and location (Athar and Ashraf, 2009).

Soil salinity is a major problem in the coastal region during the dry period. Soil salinity starts increasing from last week of December and reaches to its peak level in the month of March and April (≈25 dS/m), and minimum salinity (<2 dS/m) occurs in the months of July and August after the onset of the monsoon rains (Haque, 2006). Coastal soils vary widely in nature of salinity, depth and fluctuation of groundwater along with the seasonal variation in the salinity of surface water (Yan et al., 2015). Farmers mostly grow T.Aman during July-December and the lands remain fallow due to salinity development and scarcity of irrigation water during rest periods of the year.

To minimize water application losses and increase water use efficiencies (WUE) in the saline, drought prone and hilly regions of Bangladesh, modern irrigation technologies developed by Bangladesh Agricultural Research Institute (BARI) that are suitable for non-rice crops should be disseminated in the farmers' field. The promising water management technologies are: (i) drip fertigation that are recommended for high value vegetable and fruit crops, (ii) alternate furrow

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irrigation method suitable for both field crops and vegetables planted in rows, and (iii) deficit irrigation, mostly suitable for field crops like wheat, maize, mustard, sunflower, etc. Fertigation (Drip irrigation with fertilizer) can be used for growing high value vegetable and fruit crops like tomato, brinjal, cauliflower, strawberry, guava, etc. for higher yield, water productivity and economic return. Drip irrigation can increase yield of these crops and water use efficiency (WUE) by 10-19% and 16-23%, respectively as compared to furrow irrigation with a considerable amount of fertilizer (40%) and water saving (48%). This method can be demonstrated intensively in saline prone areas where freshwater availability is very scarce for irrigation. Besides, alternate furrow irrigation (AFI) technology, also suitable for the row field crops, can save irrigation water by about 35% with no loss of yield. In the areas under draught and saline stress to bring more area under cultivation. Dissemination of these technologies to the farmers will help them to harvest the benefits of water irrigation while minimizing the risk of its use for crop production and to increase the crop-water productivity and reduce irrigation water use in saline areas of Bangladesh.

## Materials and Method

The experiments were conducted at different locations of Southern districts named Patuakhali, Borguna, Bhola, Noakhali, and khulna. In Patuakhali district, there were 6 AFI experiments and 3 drip irrigation experiments in 2019-2020 whereas 7 AFI experiments and 3 drip irrigation experiments were carried out in 2020-2021. there were 2 AFI experiments and 2 drip irrigation experiments conducted in 2021-2022. At Borguna district there were one drip irrigation experiments for 2019-2020, 2020-2021 and 2021-2022 growing seasons. Although two drip irrigation experiments were conducted in khulna district for 2019-2020, there were no drip irrigation experiments in Khulna district in 2020-2021. In Bhola district, 3 solar powered drip irrigation experiments were conducted during both 2020-2021 and 2021-2022 growing season. One solar powered drip irrigation experiment was also conducted in Noakhali district during 2020-2021 and 2021 and 2022. In addition, 6 solar powered irrigation pumps and 6 solar panels were provided to 30 farmers of the Kaliganj upazilla, Satkhira district in order to facilitate irrigation in the Gher boundaries and during 2021-2022 six sets of drip irrigation systems were provided to Kaliganj upazilla, Satkhira to facilitate the irrigation in Gher boundaries. The location wise experiments and crops details for the 2019-2020, 2020-2021 and 2021-2022 growing seasons are presented in Tables 1, 2 and 3, respectively.

Table 1. Location wise Experiemnts and Crop/Variety details in 2019-2020 growing season

| District | Upazila | Village | Crop | Variety | Technology used |
|---|---|---|---|---|---|
| Patuakhali | Kalapara | Noyapara | Maize | BHM-9 | AFI |
| | Kalapara | Noyapara, Nobinpur, Diaramkhola, Maithvanga | Sunflower | BARI Surzomukhi-2 | AFI |
| | Kalapara | Azimpur | Watermelon | Jaguar Jumbo | Drip |
| Borguna | Amtali | Ghotkhali | Brinjal | Hybrid | Drip |
| Khulna | Koyra | 3 no koyra | Tomato | BARI tomato-21 BARI hybrid tomato-5 | Drip |
| | Koyra | 3 no koyra | Watermelon | Jaguar Jamboo | Drip |

Location wise crop, sowing/planting and harvesting dates along with the treatments are shown in Tables 4, 5 and 6 for the growing seasons 2019-2020, 2020-2021 and 2021-2022, respectively. The fertilizers were applied as per BARI recommended dose. The following data were collected from the selected plant samples from each plot.

- Plant population
- Plant height/ Vine length (cm)
- Cob per plant/ Number of fruit per plant
- Individual fruit weight (gm)

- Cob length/fruit length (cm)
- Fruit diameter (cm)
- Number of seeds per cob/ Number of seeds per head
- 1000 seed weight/100 seed weight (gm)
- Plot yield (t/ha)
- Salinity data (ds/m)

Table 2. Location wise Experiemnts and Crop/Variety details in 2020-2021 growing season

| Farmer's name | Location | Area covered, decimal | Crop | Variety | Technology used |
|---|---|---|---|---|---|
| Md. Mosharaf Gazi | Azimpur, Kuakata, Patuakhali | 33 | Watermelon | Big family | Drip |
| Md. Delowar Mridha | Azimpur, Kuakata, Patuakhali | 33 | Watermelon | Big family | Drip |
| Md. Mohibul Musulli | Azimpur, Kuakata, Patuakhali | 33 | Watermelon | Big family | Drip |
| Md. Sarowar hossain | Kalapara, Kuakata, Patuakhali | 33 | Maize | BHM-9 | AFI |
| Md. Amir Hossain | Tulatoli, Kuakata, Patuakhali | 33 | Maize | BHM-9 | AFI |
| Md. Abdur Rashid | Noyapara, Kuakata, Patuakhali | 33 | Maize | BHM-9 | AFI |
| Babul Miah | Fasipara, Kuakata, Patuakhali | 33 | Maize | BHM-9 | AFI |
| Jolil Miah & Halim Miah | Fasipara, Kuakata, Patuakhali | 66 | Maize | BHM-9 | AFI |
| Abu Saleh | Fasipara, Kuakata, Patuakhali | 66 | Sunflower | BAR Surjomukhi -2 | AFI |
| Bahadur Miah | Fasipara, Kuakata, Patuakhali | 66 | Sunflower | BAR Surjomukhi -2 | AFI |
| Jalal Mridha | Fasipara, Kuakata, Patuakhali | 66 | Sunflower | BAR Surjomukhi -3 | AFI |
| Md. Liton Shikder | Ghotkhali, Amtoli, Barguna | 28 | Brinjal | BARI Bt. Brinjal -4 | Drip |
| Md. Rasel Miah | Halimabad, charfashion, Bhola | 24 | Brinjal | BARI Bt. Brinjal -4 | Drip |
| Md. Akhtar Hossain | Halimabad, charfashion, Bhola | 28 | Sweet Gourd | BARI Mistikumra -2 | Drip |
| Md. Idris Miah | Halimabad, charfashion, Bhola | 24 | Tomato | BARI Tomato -15 | Drip |
| Md Saiful Islam | Banglabazar, Dharmapur, Noakhali Sadar | 62 | Watermelon | Jaguar Jumbo | Drip |

Table 3. Location wise Experiemnts and Crop/Variety details in 2021-2022 growing season

| Farmer's name | Location | Area covered, decimal | Crop | Variety | Technology used |
|---|---|---|---|---|---|
| Md. Mosharaf Gazi | Azimpur, Kuakata, Patuakhali | 33 | Watermelon | Big family | Drip |
| Md. Delowar Mridha | Azimpur, Kuakata, Patuakhali | 33 | Watermelon | Big family | Drip |
| Bahadur Miah | Fasipara, Kuakata, Patuakhali | 33 | Sunflower | BAR Surjomukhi -3 | AFI |
| Md. Kabir Hossain | Fasipara, Kuakata, Patuakhali | 33 | Sunflower | BAR Surjomukhi -3 | AFI |
| Md. Liton Shikder | Ghotkhali, Amtoli, Barguna | 28 | Brinjal | BARI Bt. Brinjal -4 | Drip |
| Md. Rasel Miah | Halimabad, charfashion, Bhola | 24 | Brinjal | BARI Bt. Brinjal -4 | Drip |
| Md. Akhtar Hossain | Halimabad, charfashion, Bhola | 28 | Sweet Gourd | BARI Mistikumra -2 | Drip |
| Md. Idris Miah | Halimabad, charfashion, | 24 | Tomato | BARI Tomato -15 | Drip |

| | | | | | |
|---|---|---|---|---|---|
| | Bhola | | | | |
| Md Mainuddin | Char wabda, Subarnachar, Noakhali | 62 | Watermelon | Jaguar Jumbo | Drip |
| Md. Abdus Sabur Biswas | Bharashimla, Kaliganj, Satkhira | 15 | Tomato | Hybrid (Raja) | Drip |
| Md. Aksed Ali Biswas | Bharashimla, Kaliganj, Satkhira | 10 | Tomato | Hybrid (Raja) | Drip |
| Md. Aksed Ali Biswas | Bharashimla, Kaliganj, Satkhira | 10 | Cabbage | Hybrid | Drip |
| Md. Jakir Hossain | Bharashimla, Kaliganj, Satkhira | 15 | Tomato | Hybrid (Raja) | Drip |
| Md. Jakir Hossain | Bharashimla, Kaliganj, Satkhira | 15 | Brinjal | BARI Begun-4 | Drip |
| Md. Ruhul Kuddus Gazi | Bharashimla, Kaliganj, Satkhira | 12 | Tomato | Hybrid (Raja) | Drip |

Table 4. Location wise sowing, harvesting dates and the treatments of different crops in 2019-2020

| Upazila | Crop | Date of Sowing/ Planting | Date of Harvesting | Treattments |
|---|---|---|---|---|
| Kalapara | Maize | 30.12.2019 | 25.05.2020 | $T_1$= Alternet Farrow Irrigaion (AFI)<br>$T_2$= Farmer Practice (FP) |
| Kalapara | Sunflower | 24.12.2019 | 08.04.2020 | $T_1$= AFI<br>$T_2$= FP |
| Kalapara | Watermelon | 10.01.2020 | 05.04.2020 | $T_1$= Solar Powered Drip Irrigation<br>$T_2$= FP |
| Amtali | Brinjal | 10.12.2020 | 19.05.2020 | $T_1$= Solar Powered Drip Irrigation<br>$T_2$= FP |
| Koyra | Tomato | 27.11.2019 | 27.03.2020 | $T_1$= Solar Powered Drip Irrigation<br>$T_2$= FP |
| Koyra | Watermelon | 12.01.2020 | 03.04.2020 | $T_1$= Solar Powered Drip Irrigation<br>$T_2$= FP |

Table 5. Location wise sowing, harvesting dates and the treatments of different crops in 2020-2021

| Location | Crop | Date of Sowing/ Planting | Date of Harvesting | Treatments |
|---|---|---|---|---|
| Azimpur | Watermelon | 12.12.2020 | Multiple | $T_1$= Solar Powered Drip Irrigation (SPDI)<br>$T_2$= Farmers' Practice (FP) |
| | Do | 25.12.2020 | Multiple | $T_1$= SPDI<br>$T_2$= FP |
| | Do | 28.12.2020 | Multiple | $T_1$= SPDI<br>$T_2$= FP |
| Kalapara | Maize | 15.12.2020 | 15.05.2021 | $T_1$= Alternet Farrow Irrigaion (AFI)<br>$T_2$= FP |
| Tulatoli | Do | 17.12.2020 | 20.05.2021 | $T_1$= AFI<br>$T_2$= FP |
| Noyapara | Do | 20.12.2020 | 25.05.2021 | $T_1$= AFI<br>$T_2$= FP |
| Fasipara | Do | 20.12.2020 | 24.05.2021 | $T_1$= AFI<br>$T_2$= FP |
| | Do | 20.12.2020 | 23.05.2021 | $T_1$= AFI<br>$T_2$= FP |
| | Do | 22.12.2020 | 26.05.2021 | $T_1$= AFI<br>$T_2$= FP |
| | Sunflower | 24.12.2020 | 09.04.2021 | $T_1$= AFI<br>$T_2$= FP |
| | Do | 05.01.2021 | 22.05.2021 | $T_1$= AFI<br>$T_2$= FP |
| | Do | 27.12.2020 | 11.04.2021 | $T_1$= AFI |

| | | | | |
|---|---|---|---|---|
| | | | | $T_2$= FP |
| Amtoli | Brinjal | 30.11.2020 | Multiple | $T_1$= SPDI<br>$T_2$= FP |
| Bhola | Brinjal | 12.01.2021 | Multiple | $T_1$= SPDI<br>$T_2$= FP |
| | Sweet gourd | 23.01.2021 | Multiple | $T_1$= SPDI<br>$T_2$= FP |
| | Tomato | 26.12.2020 | Multiple | $T_1$= SPDI<br>$T_2$= FP |
| Noakhali | Watermelon | 12.12.2020 | Multiple | $T_1$= SPDI<br>$T_2$= FP |

Table 6. Location wise sowing, harvesting dates and the treatments of different crops in 2021-2022

| Location | Crop | Date of Sowing/ Planting | Date of Harvesting | Treatments |
|---|---|---|---|---|
| Azimpur | Watermelon | 02.01.2022 | Multiple | $T_1$= Solar Powered Drip Irrigation (SPDI)<br>$T_2$= Farmers' Practice (FP) |
| | Do | 02.01.2022 | Multiple | $T_1$= SPDI<br>$T_2$= FP |
| Kalapara | Sunflower | 04.01.2022 | 17.04.2022 | $T_1$= AFI<br>$T_2$= FP |
| | Do | 04.01.2022 | 22.04.2022 | $T_1$= AFI<br>$T_2$= FP |
| Amtoli | Brinjal | 30.11.2022 | Multiple | $T_1$= SPDI<br>$T_2$= FP |
| Bhola | Brinjal | 12.01.2022 | Multiple | $T_1$= SPDI<br>$T_2$= FP |
| | Sweet gourd | 12.01.2022 | Multiple | $T_1$= SPDI<br>$T_2$= FP |
| | Tomato | 17.12.2022 | Multiple | $T_1$= SPDI<br>$T_2$= FP |
| Noakhali | Watermelon | 17.01.2022 | Multiple | $T_1$= SPDI<br>$T_2$= FP |
| Satkhira | Tomato | 15.12.2021 | Multiple | $T_1$= SPDI<br>$T_2$= FP |
| | Tomato | 05.12.2021 | Multiple | $T_1$= SPDI<br>$T_2$= FP |
| | Cabbage | 05.12.2021 | Multiple | $T_1$= SPDI<br>$T_2$= FP |
| | Tomato | 07.11.2021 | Multiple | $T_1$= SPDI<br>$T_2$= FP |
| | Brinjal | 07.11.2021 | Multiple | $T_1$= SPDI<br>$T_2$= FP |
| | Tomato | 07.11.2021 | Multiple | $T_1$= SPDI<br>$T_2$= FP |

***Solar Irrigation System***

In this project, IWM division used solar powered drip irrigation system. Solar power is free of cost. The installation cost was little higher, but it was less than an LLP installation cost. Farmers can use this portable solar panel for charging their home system. At the coastal region solar powered home system is available at every house. So, farmers can use this portable solar panel for multiple purposes. The specification and cost of solar irrigation system was given below.

| Item | Specification | Amount | Unit Price (BDT) | Total Cost BDT) |
|---|---|---|---|---|
| Solar Panel | 300 watts | 1 | 32 | 9600 |
| Pump | 180 watts | 1 | 4500 | 4500 |
| Accessories | - | - | - | 500 |
| | | | **Total**- | 14600 |

## Results and Discussion

The results obtained in the experiment have been presented in this section under relevant headings and sub-headings with necessary tables. The effects of different irrigation practices on different crops have been elaborated. Findings on crop yield and yield attributing characters of the growing season 2019-2020 are presented in Tables 5 through 10. Results of 2020-2021 are presented following the results of 2019-2020.

Table 7 shows the yield and yield components of maize at Kalapara upzilla under Patuakhali district. The plant population, plant height, cob length, number of seeds per cob, 100 seed weight and yield were found highest (7.50, 255.45 cm, 19.95 cm, 474.30, 25.63 g and 9.01 t/ha) in treatment $T_1$. AFI gave the highest result in all farmer fields. The yield of maize was statistically significant among the treatments.

Table 7. Yield and yield components of maize at Kalapara upazila under Patuakhali district during 2019-2020

| Treatment | Plant Population/m2 | Plant Height (cm) | Number of Cob/Plant | Cob Length (cm) | Number of Seed/ Cob | 100 Seed Weight (gm) | Yield (t/ha) |
|---|---|---|---|---|---|---|---|
| $T_1$ | 7.50a | 255.45a | 1.00 | 19.95a | 474.30a | 25.63a | 9.01a |
| $T_2$ | 7.25a | 246.98a | 1.00 | 18.40a | 461.80a | 25.18a | 8.42b |
| CV (%) | 4.79 | 6.36 | - | 6.63 | 4.92 | 2.23 | 1.71 |
| LSD | - | - | - | - | - | - | 0.34 |

Table 8 shows the yield and yield components of sunflower at Kalapara upzilla under Patuakhali district. The plant population, plant height, head diameter, number of seeds per head, 1000 seed weight and yield were found comparatively high (7.00, 143.57 cm, 59.47 cm, 464.67, 88 g and 1.99 t/ha) at treatment $T_1$. AFI performed better than conventional irrigation in all farmer fields. The head diameter, number of seed per head, 1000 seed weight and yield were statistically significant.

Table 8. Yield and yield components of sunflower at Kalapara upazila under Patuakhali district during 2019-2020

| Treatment | Plant Population/m2 | Plant Height (cm) | Head Diameter (cm) | Number of Seed/ Head | 1000 Seed Weight (gm) | Yield (t/ha) |
|---|---|---|---|---|---|---|
| $T_1$ | 7.00 | 143.57a | 59.47a | 464.67a | 88.00a | 1.99a |
| $T_2$ | 6.67 | 139.90a | 50.35b | 420.00b | 77.67b | 1.73b |
| CV (%) | - | 4.62 | 5.11 | 0.74 | 5.81 | 2.09 |
| LSD | - | - | 9.85 | 11.47 | 16.91 | 0.14 |

Table 9 shows the yield and yield components of watermelon at Kalapara upzilla under Patuakhali district. The vine length, number of fruits per plant, individual fruit weight and yield were found comparatively high (292.47 cm, 1.83, 6.18 kg and 35.51 t/ha) at treatment $T_1$. Drip irrigation performed better than conventional irrigation in all farmer fields. The vine length, and yield of watermelon were found statistically significant among the treatments.

Table 9. Yield and yield components of watermelon at kalapara upazila under patuakhali district during 2019-2020

| Treatment | Vine Length (cm) | Number of Fruits/ Plant | Individual Fruit Weight (kg) | Yield (t/ha) |
|---|---|---|---|---|
| $T_1$ | 292.47a | 1.83a | 6.18a | 35.51a |
| $T_2$ | 280.17b | 1.40a | 5.41a | 29.91b |
| CV (%) | 0.57 | 12.62 | 7.14 | 2.78 |
| LSD | 5.73 | - | - | 3.20 |

Table 10 shows the yield and yield components of BARI hybrid tomato-5 at Koyra upzilla under Khulna district. The number of fruits per plant, individual fruit weight, fruit length, fruit diameter and yield were found comparatively high (31.67, 92.33 g, 4.23 cm, 3.90 cm and 94.27 t/ha) at treatment $T_1$. Drip irrigation performed better than conventional irrigation in all farmer fields. The number of fruits per plant, fruit length, fruit diameter and yield were observed statistically significant among the treatments.

Table 10. Yield and yield components of BARI Hybrid tomato-5 at Koyra upazila under Khulna district during 2019-2020

| Treatment | Number of plant per plot | Number of fruits per plant | Individual Fruit Weight (gm) | Fruit Length (cm) | Fruit Diameter (cm) | Yield (t/ha) |
|---|---|---|---|---|---|---|
| $T_1$ | 6 | 31.67a | 92.33a | 4.23a | 3.90a | 94.27a |
| $T_2$ | 6 | 18.00b | 86.00a | 4.18b | 3.76b | 64.19b |
| CV (%) | - | 8.69 | 4.84 | 0.26 | 0.38 | 6.43 |
| LSD | - | 7.58 | - | 0.04 | 0.05 | 17.89 |

The number of fruits per plant, individual fruit weight, fruit length, fruit diameter and yield were found comparatively high (48.33, 58.33 gm, 4.26 cm, 2.51 cm and 66.72 t/ha) at treatment $T_1$. Drip irrigation performed better than conventional irrigation in all farmer fields. The number of fruits per plant, individual fruit weight and yield were statistically significant among the treatments.

Table 11. Yield and yield components of BARI tomato-21 at koyra upazila under khulna district during 2019-2020

| Treatment | Number of plant per plot | Number of fruits per plant | Individual Fruit Weight (gm) | Fruit Length (cm) | Fruit Diameter (cm) | Yield (t/ha) |
|---|---|---|---|---|---|---|
| $T_1$ | 6 | 48.33a | 58.33a | 4.26a | 2.51a | 66.72a |
| $T_2$ | 6 | 35.67b | 53.67b | 4.18a | 2.49a | 52.37b |
| CV (%) | - | 1.94 | 1.92 | 0.61 | 0.28 | 1.12 |
| LSD | - | 2.87 | 3.79 | - | - | 2.34 |

Table 12 shows the yield and yield components of watermelon at Koyra upzilla under Khulna district. The vine length, weight of fruit per plant, individual fruit weight and yield were found comparatively high (243.80, 10.02 kg, 5.01 kg and 44.48 t/ha) at treatment $T_1$. Drip irrigation performed better than conventional irrigation in all farmer fields. The vine length, weight of fruit per plant, individual fruit weight and yield were statistically significant among the treatments.

Table 12. Yield and yield components of watermelon at Koyra upazila under Khulna district during 2019-2020

| Treatment | Vine Length (cm) | Number of Fruit per Plant | Weight of Fruit per Plant (kg) | Individual Fruit Weight (kg) | Yield (t/ha) |
|---|---|---|---|---|---|
| $T_1$ | 242.80a | 2 | 10.02a | 5.01a | 44.48a |
| $T_2$ | 214.78b | 2 | 7.12b | 3.56b | 32.35b |

| | | | | | |
|---|---|---|---|---|---|
| CV (%) | 0.32 | - | 0.83 | 0.83 | 0.43 |
| LSD | 2.58 | - | 0.25 | 0.13 | 0.58 |

Findings from the demonstrations on watermelon, maize, sunflower, brinjal, sweet gourd and tomato under water saving and traditional irrigation practices carried out in various locations of the southern Bangladesh during 2020-2021 growing season are presented in brief in the subsequent paragraphs. Unlike 2019-2020, all the statistical analysis were carried out in MATLAB environment (MATLAB 2019b). The statistical inference was made through comparing the variation between groups to the variation within groups. If the ratio of between-group variation to within-group variation is significantly high, then it can be concluded that the group means are significantly different from each other. This was measured using a test statistic that has an *F*-distribution with (*k*-1, *N*-k) degrees of freedom:

$$F = \frac{SSR/_{k-1}}{SSE/_{N-k}} = \frac{MSR}{MSE} \sim F_{k-1,N-k},$$

where *MSR* is the mean squared treatment, *MSE* is the mean squared error, *k* is the number of groups, and *N* is the total number of observations. If the *p*-value for the *F*-statistic is smaller than the significance level, then the test rejects the null hypothesis that all group means are equal and concludes that at least one of the group means is different from the others. The significance level was taken as 0.05.

In Tables 13 through 20, '*F*' indicates the *F*-statistic, which is the ratio of the mean squares; and '*Prob.>F*' indicates the *p*-value, which is the probability that the *F*-statistic can take a value larger than the computed test-statistic value.

Table 13 presents the yield and yield attributing characters of watermelon at Azimpur under Patuakhali district. It is observed from Table 13 that the yield and other parameters have higher numeric values in solar powered drip irrigation treatments when compared to traditional irrigation practices. This trend indicates a superior performance of the water saving drip irrigation systems over traditional irrigation practices for watermelon production in the salinity prone southern Bangladesh. From Table 13, it is observed that number of fruits per plant (*p*-value = 0.0097<0.05) and yield (*p*-value = 0.00049<0.05) were statistically significant between the treatments.

Table 13. Yield and yield components of watermelon at Azimpur under Patuakhali district during 2020-2021

| Treatments | Vine Length (cm) | Number of Fruits/ Plant | Individual Fruit Weight (kg) | Yield (t/ha) |
|---|---|---|---|---|
| $T_1$ | 287.33 | 1.96 | 6.23 | 36.63 |
| $T_2$ | 281.67 | 1.64 | 5.89 | 28.98 |
| F | 4.66 | 21.53 | 1.71 | 346.1 |
| Prob.>F | 0.097 | 0.0097 | 0.2616 | 0.00049 |

Yield and yield attributing characters of maize at Fasipara, Patuakhali are shown in Table 14, which indicates a better performance of AFI over the traditional irrigation systems. Plant height, cob length, and number of seeds per cob were statistically significant between the treatments as indicated by the lower *p*-values than the assigned significance level. Although not statistically significant between the treatments, the yield of maize was obtained higher (8.95 t/ha) in AFI than its counterpart (8.39 t/ha).

Table 14. Yield and yield components of maize at Fasipara under Patuakhali district during 2020-2021

| Treatments | Plant Population/m2 | Plant Height (cm) | Number of Cob/Plant | Cob Length (cm) | Number of Seed/ Cob | 100 Seed Weight (gm) | Yield (t/ha) |
|---|---|---|---|---|---|---|---|

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| $T_1$ | 7.35 | 252.32 | 1 | 20.12 | 470.23 | 25.71 | 8.95 |
| $T_2$ | 7.12 | 247.61 | 1 | 18.87 | 465.17 | 25.53 | 8.39 |
| F | 5.42 | 65.1 | - | 12.7 | 14.24 | 0.34 | 2.68 |
| Prob.>F | 0.0804 | 0.0013 | - | 0.0235 | 0.0196 | 0.5925 | 0.177 |

Demonstration on sunflower at Fasipara under Patuakhali district based on AFI and traditional irrigation practice is shown in Table 15. Although the yield of sunflower was not statically significant between the treatments, the AFI approach provided higher yield of sunflower (2.31 t/ha) that the farmers' practice-based irrigation approach (2.12 t/ha). Parameters like plant height, head diameter, number of seed per head, and 1000 seed weight were found statistically significant between the treatments.

Table 15. Yield and yield components of sunflower at Fasipara under Patuakhali district during 2020-2021

| Treatments | Plant Population/m2 | Plant Height (cm) | Head Diameter (cm) | Number of Seed/ Head | 1000 Seed Weight (gm) | Yield (t/ha) |
|---|---|---|---|---|---|---|
| $T_1$ | 6.85 | 145.61 | 60.12 | 471.24 | 89.56 | 2.31 |
| $T_2$ | 6.38 | 139.85 | 53.98 | 455.32 | 81.02 | 2.12 |
| F | 3.44 | 230.6 | 153.01 | 229.85 | 114.24 | 3.09 |
| Prob.>F | 0.1374 | 0.0001 | 0.0002 | 0.0001 | 0.0004 | 0.1536 |

Table 16 shows the yield and yield components of brinjal at Amtali under Barguna district. It is perceived from Table 16 that all parameters were statistically significant between the treatments as indicated by the *p*-values lower than the threshold *p*-value of 0.05. Treatment $T_1$ (solar powered drip irrigation) produced higher value of brinjal yield (31.64 t/ha) compared to treatment $T_2$ (Farmers' practice), which produced 29.37 t/ha of brinjal yield.

Table 16. Yield and yield components of brinjal at Amtali under Barguna district during 2020-2021

| Treatments | Length of fruit, cm | Diameter of fruit, cm | Unit weight of fruit, g | Yield, t/ha |
|---|---|---|---|---|
| $T_1$ | 8.59 | 7.12 | 450 | 31.64 |
| $T_2$ | 7.12 | 6.35 | 425 | 29.37 |
| F | 116.11 | 15.87 | 12.98 | 52.84 |
| Prob.>F | 0.001 | 0.0163 | 0.0227 | 0.0023 |

Yield and yield contributing parameters of brinjal at Charfashion under Bhola district are presented in Table 17, which shows a statistically significant brinjal yield between the treatments. Treatment $T_1$ and $T_2$ produced brinjal yields of 30.64 t/ha and 27.37 t/ha, respectively. Other parameters like length of fruit and unit weight of fruit were found significantly different between the treatments.

Table 17. Yield and yield components of brinjal at Charfashion under Bhola district during 2020-2021

| Treatments | Length of fruit, cm | Diameter of fruit, cm | Unit weight of fruit, g | Yield, t/ha |
|---|---|---|---|---|
| $T_1$ | 7.53 | 6.52 | 435 | 30.64 |
| $T_2$ | 6.98 | 6.19 | 412 | 27.37 |
| F | 41.63 | 5.32 | 10.73 | 84.85 |
| Prob.>F | 0.003 | 0.0823 | 0.0306 | 0.0008 |

Parameters regarding yield and yield contributing characteristics of tomato at Charfashion under Bhola district are shown in Table 18, which indicates a relatively better performance of solar powered drip irrigation system ($T_1$) than the Farmers' practice ($T_2$) in tomato cultivation. Number of fruits per plant, individual fruit weight, and yield were found to be statistically significant between the treatments. Treatment $T_1$ produced higher tomato yield of 72.07 t/ha than treatment $T_2$ (59.45 t/ha).

Table 18. Yield and yield components of tomato at Charfashion under Bhola district during 2020-2021

| Treatment | Number of plants/plots | Number of fruits/plants | Individual Fruit Weight (gm) | Fruit Length (cm) | Fruit Diameter (cm) | Yield (t/ha) |
|---|---|---|---|---|---|---|
| $T_1$ | 6 | 50.23 | 57.39 | 4.25 | 2.48 | 72.07 |
| $T_2$ | 6 | 43.67 | 54.45 | 4.19 | 2.45 | 59.45 |
| F | - | 52.74 | 74.45 | 0.39 | 0.18 | 77.72 |
| Prob.>F | - | 0.0015 | 0.002 | 0.566 | 0.6966 | 0.0019 |

Table 19 presents yield and yield components of sweet gourd at Charfashion under Bhola district. It is observed from Table 19 that the sweet gourd production was significantly higher in treatment $T_1$ (35.83 t/ha) when compared to treatment $T_2$ (27.85 t/ha). The yields between the treatments were statistically significant. In addition, number of fruits per plant and individual fruit weights were also found statistically significant between the treatments.

Table 19. Yield and yield components of sweet gourd at Charfashion under Bhola district during 2020-2021

| Treatments | Number of fruits/plants | Individual fruit weight, kg | Yield, t/ha |
|---|---|---|---|
| $T_1$ | 4.13 | 4.82 | 35.83 |
| $T_2$ | 3.58 | 3.89 | 27.85 |
| F | 61.54 | 23.96 | 178.69 |
| Prob.>F | 0.0014 | 0.0081 | 0.0002 |

Yield and yield components of watermelon at Banglabazar under Noakhali district during 2020-2021 are presented in Table 20, which indicates that all parameters except the number of fruits per plant were statistically significant between the treatments. Treatment $T_1$ produced watermelon yield of 32.83 t/ha, which is significantly higher than the watermelon yield of 22.59 t/ha in treatment $T_2$.

Table 20. Yield and yield components of watermelon at Banglabazar under Noakhali district during 2020-2021

| Treatments | Vine Length (cm) | Number of Fruits/ Plant | Individual Fruit Weight (kg) | Yield (t/ha) |
|---|---|---|---|---|
| $T_1$ | 279.67 | 1.83 | 5.98 | 32.83 |
| $T_2$ | 258.85 | 1.78 | 4.23 | 22.59 |
| F | 14.76 | 0.83 | 57.93 | 124.8 |
| Prob.>F | 0.0184 | 0.4131 | 0.0016 | 0.0004 |

Findings from the demonstrations on watermelon, maize, sunflower, brinjal, sweet gourd and tomato under water saving and traditional irrigation practices carried out in various locations of the southern Bangladesh during 2020-2021 growing season are presented in brief in the subsequent paragraphs. Unlike 2019-2020, all the statistical analysis were carried out in MATLAB environment (MATLAB 2019b). The statistical inference was made through comparing the variation between groups to the variation within groups. If the ratio of between-group variation to within-group variation is significantly high, then it can be concluded that the group means are significantly different from each other. This was measured using a test statistic that has an *F*-distribution with (*k*-1, *N*-k) degrees of freedom:

$$F = \frac{SSR/_{k-1}}{SSE/_{N-k}} = \frac{MSR}{MSE} \sim F_{k-1,N-k},$$

where *MSR* is the mean squared treatment, *MSE* is the mean squared error, *k* is the number of groups, and *N* is the total number of observations. If the *p*-value for the *F*-statistic is smaller than the significance level, then the test rejects the null hypothesis that all group means are equal and concludes that at least one of the group means is different from the others. The significance level was taken as 0.05.

In Tables 21 through 27, '*F*' indicates the *F*-statistic, which is the ratio of the mean squares; and '*Prob.>F*' indicates the *p*-value, which is the probability that the *F*-statistic can take a value larger than the computed test-statistic value.

Table 21 presents the yield and yield attributing characters of watermelon at Azimpur under Patuakhali district. It is observed from Table 21 that the yield and other parameters have higher numeric values in solar powered drip irrigation treatments when compared to traditional irrigation practices. This trend indicates a superior performance of the water saving drip irrigation systems over traditional irrigation practices for watermelon production in the salinity prone southern Bangladesh. From Table 21, it is observed that number of fruits per plant ($p$-value = 0.0097<0.05) and yield ($p$-value = 0.00049<0.05) were statistically significant between the treatments.

Table 21. Yield and yield components of watermelon at Azimpur under Patuakhali district during 2020-2021

| Treatments | Vine Length (cm) | Number of Fruits/ Plant | Individual Fruit Weight (kg) | Yield (t/ha) |
|---|---|---|---|---|
| $T_1$ | 281.21 | 1.91 | 6.32 | 35.35 |
| $T_2$ | 279.07 | 1.60 | 5.69 | 25.89 |
| F | 4.66 | 21.53 | 1.71 | 346.1 |
| Prob.>F | 0.097 | 0.0097 | 0.2616 | 0.00049 |

Demonstration on sunflower at Fasipara under Patuakhali district based on AFI and traditional irrigation practice is shown in Table 22. Although the yield of sunflower was not statically significant between the treatments, the AFI approach provided higher yield of sunflower (2.11 t/ha) that the farmers' practice-based irrigation approach (2.02 t/ha). Parameters like plant height, head diameter, number of seed per head, and 1000 seed weight were found statistically significant between the treatments.

Table 22. Yield and yield components of sunflower at Fasipara under Patuakhali district during 2021-2022

| Treatments | Plant Population/m2 | Plant Height (cm) | Head Diameter (cm) | Number of Seed/ Head | 1000 Seed Weight (gm) | Yield (t/ha) |
|---|---|---|---|---|---|---|
| $T_1$ | 6.80 | 144.16 | 60.21 | 471.42 | 89.65 | 2.11 |
| $T_2$ | 6.31 | 138.15 | 53.89 | 455.23 | 81.02 | 2.02 |
| F | 3.44 | 230.6 | 153.01 | 229.85 | 114.24 | 3.09 |
| Prob.>F | 0.1374 | 0.0001 | 0.0002 | 0.0001 | 0.0004 | 0.1536 |

Table 23 shows the yield and yield components of brinjal at Amtali under Barguna district. It is perceived from Table 23 that all parameters were statistically significant between the treatments as indicated by the $p$-values lower than the threshold $p$-value of 0.05. Treatment $T_1$ (solar powered drip irrigation) produced higher value of brinjal yield (31.46 t/ha) compared to treatment $T_2$ (Farmers' practice), which produced 29.07 t/ha of brinjal yield.

Table 23. Yield and yield components of brinjal at Amtali under Barguna district during 2021-2022

| Treatments | Length of fruit, cm | Diameter of fruit, cm | Unit weight of fruit, g | Yield, t/ha |
|---|---|---|---|---|
| $T_1$ | 8.09 | 7.02 | 452 | 31.46 |
| $T_2$ | 7.02 | 6.05 | 427 | 29.07 |
| F | 116.11 | 15.87 | 12.98 | 52.84 |
| Prob.>F | 0.001 | 0.0163 | 0.0227 | 0.0023 |

Yield and yield contributing parameters of brinjal at Charfashion under Bhola district are presented in Table 24, which shows a statistically significant brinjal yield between the treatments.

Treatment $T_1$ and $T_2$ produced brinjal yields of 30.46 t/ha and 27.07 t/ha, respectively. Other parameters like length of fruit and unit weight of fruit were found significantly different between the treatments.

Table 24. Yield and yield components of brinjal at Charfashion under Bhola district during 2021-2022

| Treatments | Length of fruit, cm | Diameter of fruit, cm | Unit weight of fruit, g | Yield, t/ha |
|---|---|---|---|---|
| $T_1$ | 7.35 | 6.25 | 431 | 30.46 |
| $T_2$ | 6.89 | 6.09 | 411 | 27.07 |
| F | 41.63 | 5.32 | 10.73 | 84.85 |
| Prob.>F | 0.003 | 0.0823 | 0.0306 | 0.0008 |

Parameters regarding yield and yield contributing characteristics of tomato at Charfashion under Bhola district are shown in Table 25, which indicates a relatively better performance of solar powered drip irrigation system ($T_1$) than the Farmers' practice ($T_2$) in tomato cultivation. Number of fruits per plant, individual fruit weight, and yield were found to be statistically significant between the treatments. Treatment $T_1$ produced higher tomato yield of 72.00 t/ha than treatment $T_2$ (59.15 t/ha).

Table 25. Yield and yield components of tomato at Charfashion under Bhola district during 2021-2022

| Treatment | Number of plants/plots | Number of fruits/plants | Individual Fruit Weight (gm) | Fruit Length (cm) | Fruit Diameter (cm) | Yield (t/ha) |
|---|---|---|---|---|---|---|
| $T_1$ | 6 | 50.32 | 57.30 | 4.15 | 2.18 | 72.00 |
| $T_2$ | 6 | 43.57 | 54.40 | 4.09 | 2.15 | 59.15 |
| F | - | 52.74 | 74.45 | 0.39 | 0.18 | 77.72 |
| Prob.>F | - | 0.0015 | 0.002 | 0.566 | 0.6966 | 0.0019 |

Table 26 presents yield and yield components of sweet gourd at Charfashion under Bhola district. It is observed from Table 26 that the sweet gourd production was significantly higher in treatment $T_1$ (35.80 t/ha) when compared to treatment $T_2$ (27.80 t/ha). The yields between the treatments were statistically significant. In addition, number of fruits per plant and individual fruit weights were also found statistically significant between the treatments.

Table 26. Yield and yield components of sweet gourd at Charfashion under Bhola district during 2021-2022

| Treatments | Number of fruits/plants | Individual fruit weight, kg | Yield, t/ha |
|---|---|---|---|
| $T_1$ | 4.10 | 4.80 | 35.80 |
| $T_2$ | 3.50 | 3.80 | 27.80 |
| F | 61.54 | 23.96 | 178.69 |
| Prob.>F | 0.0014 | 0.0081 | 0.0002 |

Yield and yield components of watermelon at Char wabda, Subarnachar under Noakhali district during 2021-2022 are presented in Table 27, which indicates that all parameters except the number of fruits per plant were statistically significant between the treatments. Treatment $T_1$ produced watermelon yield of 32.53 t/ha, which is significantly higher than the watermelon yield of 22.59 t/ha in treatment $T_2$.

Table 27. Yield and yield components of watermelon at Char wabda, Subarnachar under Noakhali district during 2021-2022

| Treatments | Vine Length (cm) | Number of Fruits/ Plant | Individual Fruit Weight (kg) | Yield (t/ha) |
|---|---|---|---|---|
| $T_1$ | 281.67 | 1.85 | 5.12 | 32.53 |
| $T_2$ | 263.85 | 1.77 | 4.00 | 22.59 |
| F | 14.76 | 0.83 | 57.93 | 124.8 |

| Prob.>F | 0.0184 | 0.4131 | 0.0016 | 0.0004 |
|---|---|---|---|---|

***Water requirement and water productivity***

Table 28 represents the total water use during the whole season and the water productivity that represents the productivity of water in producing crop yields for the growing season 2019-2020. The water productivity for maize production was higher (1.05 kg/m$^3$) in AFI treatment than farmer practice (0.73 kg/m$^3$). The water productivity for sunflower production was higher (1.02 kg/m$^3$) in AFI treatment than farmer practice (0.51 kg/m$^3$). The water productivity for watermelon production was higher (10.30 kg/m$^3$) in drip irrigation treatment than farmer practice (7.67 kg/m$^3$). The water productivity for BARI Hybrid tomato-5 production was higher (9.58 kg/m$^3$) in drip irrigation treatment than farmer practice (5.89 kg/m$^3$). The water productivity for BARI tomato-21 production was higher (6.788 kg/m$^3$) in drip irrigation treatment than farmer practice (4.81 kg/m$^3$). Water productivity decreases with increasing quantity of water applied.

Table 28. Total water use and water productivity of different crops during 2019-2020

| Crop | Treatment | Total water use (cm) | Yield (t/ha) | Water productivity (kg/m$^3$) |
|---|---|---|---|---|
| Maize | $T_1$ | 86.01 | 9.01 | 1.05 |
| | $T_2$ | 115.4 | 8.42 | 0.73 |
| Sunflower | $T_1$ | 19.56 | 1.99 | 1.02 |
| | $T_2$ | 34.20 | 1.73 | 0.51 |
| Watermelon | $T_1$ | 58.82 | 40.00 | 6.79 |
| | $T_2$ | 70.62 | 31.13 | 4.41 |
| BARI Hybrid tomato-5 | $T_1$ | 98.38 | 94.27 | 9.58 |
| | $T_2$ | 128.84 | 64.19 | 4.98 |
| BARI tomato-21 | $T_1$ | 98.38 | 66.72 | 6.78 |
| | $T_2$ | 128.84 | 52.37 | 4.06 |

Table 29 represents the total water use during the whole season and the water productivity that represents the productivity of water in producing crop yields for the growing season 2020-2021. It is perceived from Table 29 that water productivity, in general, was observed higher in water saving irrigation treatments when compared to the Farmers' practice treatments for all cultivated crops in different locations. This attributed to the capability of producing higher yields with lower water requirements by the water saving irrigation treatments. Numeric values of the water productivity for different crops are shown in Table 29 and are not repeated in the texts. Although varied numerically, a similar trend of crop water use, yield, and hence water productivity was observed between the two growing seasons.

Table 29. Total water use and water productivity of different crops during 2020-2021

| Crop | Treatment | Total water use (cm) | Yield (t/ha) | Water productivity (kg/m3) |
|---|---|---|---|---|
| Maize | T1 | 87.73 | 8.95 | 1.02 |
| | T2 | 117.71 | 8.39 | 0.71 |
| Sunflower | T1 | 19.95 | 2.31 | 1.16 |
| | T2 | 34.88 | 2.12 | 0.61 |
| Watermelon | T1 | 60.00 | 36.63 | 6.11 |
| | T2 | 72.03 | 28.98 | 4.02 |

| | | | | |
|---|---|---|---|---|
| Tomato | T1 | 100.35 | 72.07 | 7.18 |
| | T2 | 131.42 | 59.45 | 4.52 |
| Sweet gourd | T1 | 57.36 | 35.83 | 6.25 |
| | T2 | 68.63 | 27.85 | 4.06 |
| Brinjal | T1 | 43.692 | 31.64 | 7.24 |
| | T2 | 49.555 | 29.37 | 5.93 |

Table 30 represents the total water use during the whole season and the water productivity that represents the productivity of water in producing crop yields for the growing season 2021-2022. It is perceived from Table 30 that water productivity, in general, was observed higher in water saving irrigation treatments when compared to the Farmers' practice treatments for all cultivated crops in different locations. This attributed to the capability of producing higher yields with lower water requirements by the water saving irrigation treatments. Numeric values of the water productivity for different crops are shown in Table 30 and are not repeated in the texts. Although varied numerically, a similar trend of crop water use, yield, and hence water productivity was observed among the three growing seasons.

Table 29. Total water use and water productivity of different crops during 2021-2022

| Crop | Treatment | Total water use (cm) | Yield (t/ha) | Water productivity (kg/m3) |
|---|---|---|---|---|
| Sunflower | T1 | 18.90 | 2.11 | 1.12 |
| | T2 | 30.18 | 2.02 | 0.67 |
| Watermelon | T1 | 60.50 | 33.94 | 5.61 |
| | T2 | 71.30 | 24.24 | 3.40 |
| Tomato | T1 | 98.30 | 72.00 | 7.32 |
| | T2 | 135.22 | 59.15 | 4.37 |
| Sweet gourd | T1 | 56.60 | 35.80 | 6.33 |
| | T2 | 66.16 | 27.80 | 4.20 |
| Brinjal | T1 | 41.60 | 30.96 | 7.44 |
| | T2 | 51.52 | 28.07 | 5.45 |

***Economic Analysis***

Table 31 shows the cost components and total cost of different crops and treatments of the project sites during the growing season 2019-2020. It was observed from the cost analysis that the total cost was high at farmer practice for all crops. In case of watermelon, BARI hybrid tomato-5 and BARI tomato-21 solar irrigation system were used for drip irrigation. So, the cost shown at the irrigation component for watermelon, BARI hybrid tomato-5 and BARI tomato-21 was actually the installation cost of solar irrigation system. For maize and sunflower diesel engine operated LLP was used for irrigation.

Table 31. Cost analysis of different crops and treatments of the project sites during 2019-2020

| Crop / Treatment | Land preparation (tk/ha) | Seed (tk/ha) | Fertilizer (tk/ha) | Pesticide (tk/ha) | Irrigation (tk/ha) | Labor (tk/ha) | Total Cost (tk/ha) |
|---|---|---|---|---|---|---|---|
| Maize | | | | | | | |
| $T_1$ | 9375 | 8000 | 28800 | 0 | 16000 | 38800 | 100975 |
| $T_2$ | 9375 | 8000 | 28800 | 0 | 32000 | 55000 | 133175 |
| Sunflower | | | | | | | |
| $T_1$ | 9375 | 3000 | 23400 | 0 | 24000 | 18800 | 78575 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| $T_2$ | 9375 | 3000 | 23400 | 0 | 28000 | 20000 | 83775 |
| Watermelon | | | | | | | |
| $T_1$ | 11250 | 16875 | 32400 | 30000 | 14600 | 75000 | 180125 |
| $T_2$ | 11250 | 16875 | 32400 | 30000 | 28000 | 95000 | 213525 |
| BARI Hybrid tomato-5 | | | | | | | |
| $T_1$ | 12870 | 4000 | 14790 | 5000 | 14600 | 51400 | 102660 |
| $T_2$ | 12870 | 4000 | 14790 | 5000 | 14600 | 66800 | 118060 |
| BARI tomato-21 | | | | | | | |
| $T_1$ | 12870 | 1200 | 14790 | 5000 | 14600 | 51400 | 99860 |
| $T_2$ | 12870 | 1200 | 14790 | 5000 | 14600 | 66800 | 115260 |

The total cultivation cost as well as a breakdown of individual cost items for the growing season 2020-2021 is presented in table 32. As demonstrations were performed in some new locations, the total cost reflects the inclusion of installation costs as well. The price difference was due to the variable costs of materials and labor not only between the seasons but also between the locations.

Table 32. Cost analysis of different crops and treatments of the project sites during 2020-2021

| Crop / Treatment | Land preparation (tk/ha) | Seed (tk/ha) | Fertilizer (tk/ha) | Pesticide (tk/ha) | Irrigation (tk/ha) | Labor (tk/ha) | Total Cost (tk/ha) |
|---|---|---|---|---|---|---|---|
| Sunflower | | | | | | | |
| T1 | 9563 | 3060 | 23868 | 2040 | 24480 | 19176 | 82187 |
| T2 | 9563 | 3060 | 23868 | 2040 | 28560 | 20400 | 87491 |
| Watermelon | | | | | | | |
| T1 | 11475 | 17213 | 33048 | 30600 | 14892 | 76500 | 183728 |
| T2 | 11475 | 17213 | 33048 | 30600 | 28560 | 96900 | 217796 |
| Tomato | | | | | | | |
| T1 | 13127 | 2040 | 15086 | 5100 | 15606 | 52428 | 103387 |
| T2 | 13127 | 2040 | 15086 | 5100 | 27132 | 68136 | 130621 |
| Sweet gourd | | | | | | | |
| T1 | 11475 | 1224 | 16106 | 4590 | 13872 | 56100 | 103367 |
| T2 | 11475 | 1224 | 16106 | 4590 | 24837 | 68034 | 126266 |
| Brinjal | | | | | | | |
| T1 | 10455 | 2550 | 17228 | 5610 | 17850 | 54876 | 108569 |
| T2 | 10455 | 2550 | 17228 | 5610 | 25296 | 66096 | 127235 |

The total cultivation cost as well as a breakdown of individual cost items for the growing season 2021-2022 is presented in table 33. As demonstrations were performed in some new locations, the total cost reflects the inclusion of installation costs as well. The price difference was due to the variable costs of materials and labor not only between the seasons but also between the locations.

Table 33. Cost analysis of different crops and treatments of the project sites during 2021-2022

| Crop / Treatment | Land preparation (tk/ha) | Seed (tk/ha) | Fertilizer (tk/ha) | Pesticide (tk/ha) | Irrigation (tk/ha) | Labor (tk/ha) | Total Cost (tk/ha) |
|---|---|---|---|---|---|---|---|
| Sunflower | | | | | | | |
| T1 | 9658 | 3060 | 23868 | 2040 | 25480 | 20176 | 84282 |
| T2 | 9658 | 3060 | 23868 | 2040 | 29560 | 21400 | 89586 |
| Watermelon | | | | | | | |
| T1 | 11878 | 17213 | 33048 | 30600 | 15892 | 78500 | 187131 |
| T2 | 11878 | 17213 | 33048 | 30600 | 28960 | 97900 | 219599 |
| Tomato | | | | | | | |
| T1 | 13425 | 2040 | 15086 | 5100 | 15906 | 54428 | 105985 |
| T2 | 13425 | 2040 | 15086 | 5100 | 27932 | 69136 | 132719 |
| Sweet gourd | | | | | | | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| T1 | 11875 | 1224 | 16106 | 4590 | 14472 | 58300 | 106567 |
| T2 | 11875 | 1224 | 16106 | 4590 | 25237 | 69030 | 128062 |
| Brinjal | | | | | | | |
| T1 | 10955 | 2550 | 17228 | 5610 | 18750 | 55825 | 110918 |
| T2 | 10955 | 2550 | 17228 | 5610 | 26225 | 68090 | 130658 |

Table 34 shows the BCR of different crops of the project sites for the growing season 2019-2020. It was observed from table 34 that the BCR of AFI and drip irrigation system was high for all crops and the BCR for farmer practice treatment was comparatively less than the water saving technologies.

Table 34. Benefit Cost Ratio of different crops and treatments of the project sites during 2019-2020

| Crop<br>Treatment | Total Cost (tk/ha) | Total Return (tk/ha) | BCR |
|---|---|---|---|
| Maize | | | |
| $T_1$ | 100975 | 180200 | 1.78 |
| $T_2$ | 133175 | 168400 | 1.26 |
| Sunflower | | | |
| $T_1$ | 78575 | 99500 | 1.27 |
| $T_2$ | 83775 | 86500 | 1.03 |
| Watermelon | | | |
| $T_1$ | 180125 | 400000 | 2.22 |
| $T_2$ | 213525 | 311300 | 1.46 |
| BARI Hybrid tomato-5 | | | |
| $T_1$ | 102660 | 282810 | 2.75 |
| $T_2$ | 118060 | 192570 | 1.63 |
| BARI tomato-21 | | | |
| $T_1$ | 99860 | 200160 | 2.00 |
| $T_2$ | 115260 | 157110 | 1.36 |

Table 35 presents the BCR of different crops of the project sites for the growing season 2020-2021. As indicated by Tables 34 and 35, the BCR followed the similar trend between the two growing seasons despite a difference in numeric values.

Table 35. Benefit Cost Ratio of different crops and treatments of the project sites during 2020-2021

| Crop<br>Treatment | Total Cost (tk/ha) | Total Return (tk/ha) | BCR |
|---|---|---|---|
| Maize | | | |
| T1 | 106055 | 185606 | 1.75 |
| T2 | 138899 | 173452 | 1.25 |
| Sunflower | | | |
| T1 | 82187 | 102485 | 1.25 |
| T2 | 87491 | 89095 | 1.02 |
| Watermelon | | | |
| T1 | 183728 | 412000 | 2.24 |
| T2 | 217796 | 320639 | 1.47 |
| Tomato | | | |
| T1 | 103387 | 291294 | 2.82 |
| T2 | 130621 | 198347 | 1.52 |
| Sweet gourd | | | |
| T1 | 103367 | 206165 | 1.99 |
| T2 | 126266 | 161823 | 1.28 |
| Brinjal | | | |
| T1 | 108569 | 309165 | 2.85 |
| T2 | 127235 | 264823 | 2.08 |

Table 36 presents the BCR of different crops of the project sites for the growing season 2021-2022. As indicated by Tables 34, 35 and 36, the BCR followed the similar trend between the two growing seasons despite a difference in numeric values.

Table 36. Benefit Cost Ratio of different crops and treatments of the project sites during 2021-2022

| Crop / Treatment | Total Cost (tk/ha) | Total Return (tk/ha) | BCR |
|---|---|---|---|
| Sunflower | | | |
| T1 | 84282 | 93611.84 | 1.11 |
| T2 | 89586 | 84892.41 | 0.95 |
| Watermelon | | | |
| T1 | 187131 | 381743.93 | 2.04 |
| T2 | 219599 | 268194.94 | 1.22 |
| Tomato | | | |
| T1 | 105985 | 291011.07 | 2.75 |
| T2 | 132719 | 197346.09 | 1.49 |
| Sweet gourd | | | |
| T1 | 106567 | 205992.38 | 1.93 |
| T2 | 128062 | 161532.47 | 1.26 |
| Brinjal | | | |
| T1 | 110918 | 302520.49 | 2.73 |
| T2 | 130658 | 253101.18 | 1.94 |

## Conclusion

The experiments were conducted through Small Holder Agricultural Competitiveness Project (SACP) jointly funded by IFAD and GoB. The project sites were at the coastal region of Bangladesh. Two water saving irrigation technologies (Alternate Farrow Irrigation and Solar Powered Drip Irrigation) were demonstrated at the farmers' field. The farmers were benefited and interested to use these types of water saving technologies. Farrow Irrigation and Solar Powered Drip Irrigation has given better result than farmer practice and the BCR of those water saving technologies were remain high than the existing farmer practice. As we know that the southern districts of Bangladesh are suffering from shortage of water and fresh irrigation water at the Rabi season to grow winter crops. So, we need to disseminate these two promising water saving irrigation technologies covering a range of locations within the salt affected southern parts of Bangladesh. The findings not only provide a valuable insight regarding crop production under water scarcity but also motivate the farmers of the project site in using water saving irrigation technologies to achieve higher yields.

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## Appendix: I At a Glance
## Irrigation and Water Management Division, BARI, Gazipur

**Establishment**

Irrigation and Water Management Division is one of the 17 research divisions of BARI. It has been created as a full flazed division after dividing Agricultural Engineering Division in 1990. Presently, the division is headed by a Chief Scientific Officer along with 07 scientists of agricultural engineering disciplines. It is devoted to contribute in increasing the yield and production of agricultural crops through the promotion of irrigation and the improvement of water resources management for sustainable agriculture. By this time, this division has developed about 51 irrigation and water management technologies of which most of them are being used at the field level.

## Appendix: II

## List of the Scientists and Scientific Staffs Involved in IWM Research Program during 2021-2022

| SL. No. | Name | Designation |
|---|---|---|
| 1 | Dr. Md. Anower Hossain | Chief Scientific Officer (in-charge) & Head |
| 2 | Dr. Sujit Kumar Biswas | Principal Scientific Officer |
| 3 | Dr. Dilip Kumar Roy | Senior Scientific Officer |
| 4 | Dr. Afrin Janah Mila | Senior Scientific Officer |
| 5 | Farzana Akter | Scientific Officer |
| 6 | SK. Shamshul Alam Kamar | Scientific Officer |
| 7 | Md. Jubair Hasan | Assistant Agricultural Engineer |
| 8 | Md. Kamal Hossain | Scientific Assistant |
| 9 | Md. Enayet Sharif | Scientific Assistant |
| 10 | Mostafa Kamal | Scientific Assistant |
| 11 | Mohammad Samim Miah | UDA |
| 12 | Md. Abul Kalam | Office Assistant Cum-computer Operator |
| 13 | Md. Jahirul Islam | Surveyor |
| 14 | Md. Monayem Kabir | Laboratory Attendant |

## Appendix: III কর্মসম্পাদন সূচক, লক্ষ্যমাত্রা এবং অর্জন ২০২১-২২ (সেকশন -৩)

| ক্রমিক নং | সূচক | একক | লক্ষ্যমাত্রা ২০২১-২২ | অর্জন ২০২১-২২ |
|---|---|---|---|---|
| ১ | ১.১.৩ উদ্ভাবিত প্রযুক্তি | সংখ্যা | ১ | ১ |
| ২ | ১.২.১ প্রশিক্ষিত কৃষক | সংখ্যা | ৯০ | ৯০ |
| ৩ | ১.২.৩ স্থাপিত প্রদর্শনী | সংখ্যা | ৫ | ৫ |
| ৪ | ১.২.৪ আয়োজিত সেমিনার/ওয়ার্কশপ | সংখ্যা | ১ | ১ |
| ৫ | ১.২.৫ আয়োজিত মাঠ দিবস/ র‍্যালী | সংখ্যা | ২ | ২ |
| ৬ | ১.২.৭ হস্তান্তরিত প্রযুক্তি | সংখ্যা | ১ | ১ |
| ৭ | ১.২.৮ বার্ষিক গবেষণা রিপোর্ট প্রকাশিত | সংখ্যা | ১ | ১ |
| ৮ | ১.২.৯ লিফলেট, নিউজলেটার, বুকলেট, জার্নাল ইত্যাদি প্রকাশিত | সংখ্যা | ১ | ৩ |
| ৯ | ২.২.৩ মুজিব বর্ষ উপলক্ষ্যে কৃষকের মাঠে প্রদর্শনী স্থাপিত | সংখ্যা | ১ | ১ |
| ১০ | ২.৭.১ উদ্ভাবিত প্রযুক্তি সমূহের প্রদর্শনী স্থাপিত | সংখ্যা | ৫ | ৫ |
| ১১ | ২.৭.২ প্রযুক্তি ব্যবহারে সহযোগিতা প্রদান | সংখ্যা | ২ | ২ |
| ১২ | ৩.১.১ বিশ্লেষিত মাটি, পানি, উদ্ভিদ, সার, বালাইনাশক ইত্যাদি | সংখ্যা | ১০০ | ১০০ |
| ১৩ | ৩.১.৩ জৈবসার (কম্পোস্ট ও ভার্মিকম্পোস্ট) উৎপাদিত | কেজি | ১০০ | ১০০ |
| ১৪ | ৫.১.২ কর্মকর্তাদের পরিদর্শনকৃত অনুন্নয়ন বাজেটের আওতায় কার্যক্রম | সংখ্যা | ১ | ১ |

**Appendix: IV Rainfall Data at Gazipur location in mm (From July 2021 to June 2022)**

| Date | July/ 2021 | August/ 2021 | September/ 2021 | October/ 2021 | November/ 2021 | December/ 2021 | January/ 2022 | February/ 2022 | March/ 2022 | April/ 2022 | May/ 2022 | June/ 2022 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 30 | 4 | 4 | 0 | 0 | 0 | 0 | 0 | 0 | **0** | 0 | 4 |
| 2 | 129 | 33 | 24 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 63 |
| 3 | 6 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 21 | 0 |
| 4 | 41 | 7 | 2 | 9 | 0 | 0 | 0 | 25 | 0 | 0 | 3 | 0 |
| 5 | 39 | 0 | 0 | 9 | 0 | 3 | 0 | 11 | 0 | 0 | 1 | 0 |
| 6 | 0 | 44 | 3 | 8 | 0 | 72 | 0 | 0 | 0 | 0 | 5 | 2 |
| 7 | 4 | 14 | 0 | 10 | 0 | 4 | 0 | 0 | 0 | 0 | 160 | 8 |
| 8 | 0 | 31 | 2 | 0 | 0 | 4 | 0 | 0 | 0 | 0 | 134 | 0 |
| 9 | 0 | 12 | 0 | 0 | 0 | 53 | 0 | 0 | 0 | 0 | 319 | 18 |
| 10 | 1 | 16 | 0 | 0 | 0 | 113 | 0 | 0 | 0 | 0 | 57 | 0 |
| 11 | 0 | 14 | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 30 | 0 |
| 12 | 7 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 21 | 0 |
| 13 | 0 | 40 | 0 | 0 | 4 | 0 | 0 | 0 | 0 | 0 | 22 | 12 |
| 14 | 0 | 5 | 2 | 0 | 9 | 0 | 0 | 0 | 0 | 0 | 2 | 0 |
| 15 | 0 | 0 | 0 | 0 | 4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 16 | 46 | 0 | 5 | 8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 17 | 9 | 1 | 4 | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 10 | 95 |
| 18 | 1 | 2 | 0 | 10 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 22 |
| 19 | 5 | 2 | 3 | 17 | 0 | 0 | 0 | 0 | 0 | 39 | 0 | 9 |
| 20 | 6 | 3 | 0 | 16 | 0 | 0 | 0 | 0 | 0 | 10 | 30 | 7 |
| 21 | 5 | 32 | 3 | 3 | 0 | 0 | 0 | 0 | 0 | 1 | 22 | 31 |
| 22 | 9 | 27 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 5 | 0 |
| 23 | 1 | 20 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| 24 | 6 | 27 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 38 | 0 |
| 25 | 12 | 77 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 24 | 1 |
| 26 | 0 | 25 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 5 | 0 |
| 27 | 10 | 8 | 0 | 0 | 0 | 0 | 0 | 0 | 15 | 0 | 0 | 0 |
| 28 | 2 | 0 | 8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 10 | 2 |
| 29 | 8 | 11 | 0 | 0 | 0 | 0 | 0 | - | 6 | 0 | 0 | 4 |
| 30 | 10 | 0 | 8 | 0 | 0 | 0 | 0 | - | 4 | 0 | 0 | 10 |
| 31 | 14 | 3 | - | 0 | - | 0 | 0 | - | 1 | - | 7 | |

# Appendix: V List of Publication (January 2021 to June 2022)

**Roy, D. K.**, Sarkar, T. K., **Kamar, S. S. A.**, Goswami, T., Muktadir, M. A., Al-Ghobari, H. M., ... & Mattar, M. A. (2022). Daily Prediction and Multi-Step Forward Forecasting of Reference Evapotranspiration Using LSTM and Bi-LSTM Models. *Agronomy*, *12*(3), 594.

**Mila, A. J.**, Bell, R. W., Barrett-Lennard, E. G., & Kabir, M. E. (2021). Salinity dynamics and water availability in water bodies over a dry season in the Ganges Delta. *Future of sustainable agriculture in saline environments*, 305-322.

**HAQUE, M. P.**, & FAISAL, S. M. (2021). Yield, crop water productivity and economic benefit of bottle gourd (Lagenaria siceraria) production in response to irrigation. *Journal of Global Agriculture and Ecology*, 12(1), 9-17.

**Haque, M. P.**, Hossain, M. Z., & Ali, M. A. (2021). Climate Change Effect on Irrigation Water Requirement of Wheat and Maize in Northern Part of Bangladesh. *International Journal of Climate Research*, *5*(1), 25-34.

**Roy, D. K.**, Biswas, S. K., Saha, K. K., & **Murad, K. F. I**. (2021). Groundwater Level Forecast via a Discrete Space-State Modelling Approach as a Surrogate to Complex Groundwater Simulation Modelling. *Water Resources Management*, *35*(6), 1653-1672.

**Roy, D. K.** (2021). Long short-term memory networks to predict one-step ahead reference evapotranspiration in a subtropical climatic zone. *Environmental Processes*, *8*(2), 911-941.

**Roy, D. K.**, Lal, A., Sarker, K. K., Saha, K. K., & Datta, B. (2021). Optimization algorithms as training approaches for prediction of reference evapotranspiration using adaptive neuro fuzzy inference system. *Agricultural Water Management*, *255*, 107003.

**Roy, D.K., Biswas, S.K.,** Mattar, M.A., El-Shafei, A.A., **Murad, K.F.I.**, Saha, K.K., Datta, B., Dewidar, A.Z., 2021. Groundwater Level Prediction Using a Multiple Objective Genetic Algorithm-Grey Relational Analysis Based Weighted Ensemble of ANFIS Models. *Water*, 13*(21)*: 3130. https://doi.org/10.3390/w13213130

**Roy, D. K.**, Saha, K. K., Kamruzzaman, M., **Biswas, S. K.**, & **Hossain, M. A.** (2021). Hierarchical fuzzy systems integrated with particle swarm optimization for daily reference evapotranspiration prediction: A novel approach. *Water Resources Management*, *35*(15), 5383-5407.

Mojid, M.A., Mainuddin, M., **Murad, K.F.I.** and Kirby, J.M., 2021. Water Usage Trends under Intensive Groundwater-Irrigated Agricultural Development in a Changing Climate – Evidence from Bangladesh. *Agricultural Water Management*, *251*, p.106873.

Peña-Arancibia, J.L., Mahboob, M.G., Islam, T., Mainuddin, M., Yu, Y., Ahmad, M.D., **Murad, K.F.I.**, Saha, K., Hossain, A., Moniruzzaman, M., Ticehurst, T. and Kong, D., 2021. The Green Revolution from space: mapping the historic dynamics of main rice types in one of the world's food bowls. *Remote Sensing Applications: Society and Environment*, *21*, p.100460.

Islam, H. T., Islam, A. R. M. T., Shahid, S., Alam, G. M., Biswas, J. C., Rahman, M. M., **Roy, D.K.** & Kamruzzaman, M. (2022). Future precipitation projection in Bangladesh using SimCLIM climate model: A multi- model ensemble approach. *International Journal of Climatology*.

Kamruzzaman, M., Shahid, S., **Roy, D. K.**, Islam, A. R. M. T., Hwang, S., Cho, J., ... & **Akter, F.** (2022). Assessment of CMIP6 global climate models in reconstructing rainfall climatology of Bangladesh. *International Journal of Climatology*, *42*(7), 3928-3953.

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