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Are there any 'hot spots' and 'bright spots' of rice water productivity in Bangladesh? A spatio-temporal analysis of district-level data

Alternative title: Are there any 'hot spots' and 'bright spots' of rice water productivity in Bangladesh? A spatio-temporal analysis focusing on the Ganges-dependent vis-à-vis other districts.

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Abstract

Employing Bangladeshi district-level time series data as an empirical exploration this paper aims to: (1) estimate two measures of rice water productivity for the main crop seasons; (2) undertake a spatio-temporal analysis; and (3) identify 'hot spots' and 'bright spots' focusing on the Ganges-dependent (GDA) vis-à-vis other districts (NGDA).

The paper finds that (1) kharif (wet) season rice water productivity grew much faster than for the rabi (dry) season across all districts. There was no significant correlation between seasonal growth rates although significant correlation existed between seasonal growth rates and the annual growth rate. Eight Ganges dependent districts experienced faster growth rate in kharif and overall productivity but their rabi season performance was slower relative to other districts. (2) Marginal productivity (MP) experienced fastest growth for the kharif season during 1968-1980. Up to 1990, there was no significant growth in rabi MP. Its growth declined in the 1980s but picked up since the early 1990s. (3) MPs products were slightly lower in the GDA districts for kharif and overall. The study did not find any consistent 'hot spots' or 'bright spots' in Bangladeshi rice water productivity. The process is highly groundwater intensive and is debatable whether it is sustainable.

Key words: Water productivity; internal land augmentation, Ganges dependent area; Consumptive water use, groundwater usage.

JEL classification: O1, Q0, Q2.

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1. INTRODUCTION

While the existing literature on agricultural development has focused extensively on land productivity, little attention has been paid to measuring water productivity in agriculture especially in apparently water-abundant countries like Bangladesh. This is despite the fact that water has been the critical input in the intensification of agriculture in may parts of the world especially South Asia, since the introduction of the seed-fertilizer-irrigation technology, commonly known as the green revolution more than four decades ago. Given that water is a limiting factor for crop production in many parts of the world and, therefore, food security, measuring water productivity thus assumes critical importance.

Of late, however, researchers at the International Water Management Institute (IWMI) have broken new grounds in measuring water accounts and crop water productivity on different scales (see for example, Ahmad et al 2004; Barker et al 2003; Cai and Rosegrant 2003; Molden et al 2001; Molden et al 2003; Molden and Sakthivadivel 1999). However, the available literature, crop water productivity concentrates in the main on static cross-section analysis and uses aggregate data with occasional micro-level evidence (Molden et al. 2007), even though different scenarios are considered between two points in time e.g. 2000 and 2025 (Cai and Rosegrant 2003). Thus the available literature to date has paid little attention to disaggregated (e.g. district-level) analysis involving long-term time series data.

This study aims to fill this gap by employing district-level time series data for the rice crop Bangladesh as a case study involving 21 districts and 37 years. Two measures of water productivity, average and marginal, are estimated using rice output and consumptive water use (CWU) data for the two main crop seasons – *rabi* (dry, groundwater irrigated) and *kharif* (summer and autumn, rainfed with supplementary irrigation where possible) and annually by districts.

The rationale for using rice as a case study rests on the fact that even though Bangladesh grows a large number of crops, rice is by far the most dominant and bulk of the crop water use is confined to rice production. Furthermore, the data for rice are more readily available than for other crops. However, one could extend this methodology to other crops.

This paper builds on the IWMI research and extends it to dynamic contexts by (1) undertaking a spatio-temporal analysis of these measures; (2) identifying 'hot spots' and 'bright spots' using GIS.

Of particular importance is the focus on the relative performances of the districts that constitute the Ganges-dependent area (GDA) vis-à-vis the remaining districts (NGDA) of Bangladesh. The rationale for the focus on GDA rests on several grounds:

- This research is part of International Water Management Institute – Indo-Gangetic Basin (IWMI-IGB) project.
- The process of agricultural intensification as measured by the incidence of multiple cropping has experienced the fastest growth between the early 1970s and 2004.
- The GDA has witnessed a major increase in minor irrigation following increasing liberalization of the irrigation sector in the 1980s. At private initiatives, these small systems, based on low-lift pump (surface water), shallow and deep tube wells (STWs and DTWs, groundwater), drawing from streams and from groundwater have proliferated. After a rapid growth, LLP irrigation has slowed down quite significantly since the 1990s due to limited access to

reliable surface water supplies. This has led to development of groundwater structures in places previously served by surface water structures (WARPO 2002, p.11).

- The driest districts are located in the GDA. This region, characterized by high climatic variability, is likely to experience even greater climatic variability in coming decades. By 2050, the dry season (November-May) water deficit will rise to 24.6 per cent from 9.4 per cent in 2025. On the other hand, the wet season (June-October) water surplus will increase to 29.7 per cent from 8.85 per cent over the same period (WARPO 2002, p.13).

The paper proceeds first with a discussion of methodological issues surrounding the derivation of CWU estimates. Section 3 discusses the land-water nexus and the data used in this study. Section 4 presents the empirical results. Section 5 provides an in-depth analysis and identifies any 'hot spots' and 'bright spots' in rice water productivity and provides an exploratory explanation. Section 6 presents conclusions.

2. METHODOLOGICAL ISSUES

Significant methodological issues underlie measurement of water productivity given that such measurement involves the use of both scientific and statistical information on water requirements for crops, rainfall and evapotranspiration, irrigation, crop coefficients, and crop cycle, crop output and related data.

Vaidyanathan and Sivasubramaniyan (2004) measured changes in water demand for crop production in India between 1966 and 1991 employing consumptive water-use (CWU). Vaidyanathan and Sivasubramaniyan (2004) based their estimation of CWU on the use of mean annual rainfall and evapotranspiration (Et_p). However, Vaidyanathan and Sivasubramaniyan (2004) did not cover all the Indian states. Furthermore, it used the average annual rainfall, which masks significant interregional variations in annual rainfall, Et_p and the growth period of different crops.

Ahmad et al (2004) estimated rice and wheat water productivity in the Rechna-Doab basin in the Pakistan Punjab. Their methodology involved the use of GIS technique and scientific experiments. While this is possible for a micro-level study, it shall be rather too laborious, cumbersome, and data-intensive to investigate crop water productivity for a larger geographical entity such as country or across regions within a country or over time.

This paper measures water productivity for a particular crop or a group of crops as a ratio crop output to consumptive water use (CWU). Equation 1 (Amarasinghe et al 2007) embodies the estimation of CWU.

$$CWU_l = \begin{cases} \sum_{k \in seasons} IRA_{lk} \sum_{j \in months} \sum_{i \in growth\ periods} kc_{ki}^{l} \times ETp_j \times \frac{d_{ij}}{n_j} & \textit{for irrigated crops} \\ \sum_{k \in seasons} RFA_{lk} \sum_{j \in month} \sum_{i \in growth\ periods} \min\,(kc_{ki}^{l} \times ETp_j, Effrf_j) \times \frac{d_{ij}}{n_j} & \textit{for rain-fed crops} \end{cases} \quad (1)$$

Where IRA_{lk} and RFA_{lk} respectively represent irrigated and rainfed area of the l^{th} crop in the k^{th} season, i is the number of growth periods, generally four but could be more. d_{ij} is the number of days of the j^{th} month in the i^{th} crop growth period while n_j is the number of days of the j^{th} month; kc is the crop coefficient of the crop in the i^{th} growth period of the k^{th} season, $Effrf_j$ is the effective rainfall for the period of the month in which the crop is grown.

Equation (1) embodies two multipliers:

a. For irrigated crops it is simply the expression involving the second and the third summation signs and entails the use of crop ET_p ($=kc^l_{kl}$ x ETP_j) on the assumption that irrigation meets the full water requirements of the crops. In reality however, this may not be case. This is because in many water-scarce areas, irrigation may not meet the full water requirement. In the absence of any dependable information, the study had no alternative but to assume away irrigation water deficit.

b. For the rainfed crops, it is the minimum of (crop ET_p, $Effrf_j$).

This study calls the multiplier (a) the irrigated multiplier (*IM*) and the multiplier (b) the rainfed multiplier (*RM*).

Based on PODIUMSIM (p.9), Equation (2) estimates effective rainfall.

$$Effrf = AMR*(1- 0.25*AMR)/125 \text{ if } AMR \leq 250 \text{ or } Effrf = 125 + 0.1*AMR \text{ if } AMR \geq 250 \quad (2)$$

Where *Effrf* and *AMR* respectively represent in millimeters of effective rainfall and average monthly rainfall.

This study employs actual monthly rainfall data described in Section 3 (cf. Amarasinghe et al. 2007; Amarasinghe et al. 2005). Further discussions on methodology and definitions (and assumptions) for other parameters used in the study are taken up in Section 3.

3. LAND-WATER NEXUS IN BANGLADESH AGRICULTURE AND THE DATA

3.1 Land-Water Nexus

High population pressure and the rapid pace of human activity including urbanization, industrialization and other economic activities have led to a dwindling supply of arable land per capita and a process of agricultural intensification in South Asia generally but especially Bangladesh. As noted by Alauddin and Quiggin (2008, p.112):

> A range of innovations collectively referred to as the Green Revolution, which has increased food production significantly, has accompanied agricultural intensification. Central elements of the Green Revolution have

been the introduction of higher-yielding varieties of wheat and rice, accompanied by increased use of fertilizers and agricultural machinery. Irrigation, primarily based on groundwater has played critically important role. Most of these innovations have been land-saving, but capital-intensive and water-intensive.

In assessing developments in Bangladesh agriculture one needs to consider several broad indicators of change. Based on Alauddin and Quiggin (2008) these can be summarized as follows:

- Arable land per person in Bangladesh has considerably declined and is estimated to be 0.06 hectare recently compared to 0.16 hectare in the early 1960s.
- The proportion of land area in agricultural use in Bangladesh is the highest among the South Asian countries (around 70%).
- The incidence of irrigation (irrigated area as a percentage of arable land) has grown most rapidly in Bangladesh given its very low base in the late 1960s and currently stands at more than 50 per cent. The intensity of irrigation (measured by the gross area irrigated expressed as percentage of net area irrigated) for Bangladesh in quite high in the region and stands at 165 per cent in recent years.
- Bangladesh is the most rice-intensive country in the South Asian region, Gross cropped area allocated to rice as a percentage of arable land stands at about 140 per cent recently.
- Bangladesh has experienced the highest degree of agricultural intensification because of multiple cropping, which required a substantial increase in non-land inputs.

Overall, therefore, the focus of agricultural development in Bangladesh has shifted from a process of external land augmentation or extensive margin to one of internal land-augmentation or intensive margin (Hayami and Ruttan 1985). The overall process seems consistent with the Boserup hypothesis (1965, 1981) that increased intensity of factor use in agriculture accompanies an increase in population density. Boserup's main argument rests on the premises that (1) rising population pressure leads to intensification of farming methods in order to increase food production to support extra population; and (2) pressure to change agricultural output by modifying farming techniques primarily comes from the demand side.

The supply side response typified by the green revolution contained several episodes. It commenced with the distribution of chemical fertilizers followed subsequently by the introduction of modern irrigation techniques spearheaded by shallow and deep tube wells and low lift pumps promoting the use of ground and surface water. However, it was not until the later part of the 1960s when Bangladesh introduced high-yielding varieties of rice and wheat that the use of irrigation and chemical fertilizers assumed any real significance.

The introduction of the HYVs (biological innovations) contained elements of different types of technology transfer that involved material transfer, design transfer and capacity transfer (See for example Hayami and Ruttan 1985, pp. 260-62). In the late 1960s, IR-8, IR-5 and IR-20 of rice continued to be introduced initially through the direct import of seeds, and in the late 1960s and early 1970s HYVs of wheat was introduced. Subsequently, however, the Bangladesh agricultural research system adapted and indigenously developed strains of rice and wheat that were multiplied and released to farmers for expanded production (Alauddin and Hossain 2001, see also Alauddin and Tisdell 1991).

The green revolution in Bangladesh typified a process of commodity bias in favor of cereals and did not represent a broad-based crop revolution. The increased emphasis at the farm-level has been primarily due to (a) higher yields; (b) a substitution in favor of high yield cereals for other crops and the expansion of gross cropped area supported by expansion in dry season irrigation. Furthermore, based on cost and return surveys of major crops during 1979-1992, the higher financial profitability of HYVs relative to local rice varieties contributed to their rapid adoption and diffusion.

The characteristic feature of the expansion of irrigation is the extraordinary growth in groundwater irrigation. Based on data from various issues of Statistical yearbook of Bangladesh that out of a total irrigated area of 1.16 million hectares only 32.7 thousand hectares (2.8 per cent) originated from groundwater in 1969. This is in contrast to the 2004 scenario when 3.74 million hectares (71.9 per cent) of the total area irrigated (5.21 million hectares) were irrigated from groundwater sources. Furthermore, around 80 per cent of the gross area irrigated is attributable to rice. However, this is the average figure for Bangladesh as a whole and masks significant inter-district variation.

3.2 The Data

The data for this study warrant some discussion as they came from various scattered sources and required further processing for the derivation of water productivity measures.

- Bangladesh district-level data for 21 districts for 37 years (1968-2004) on crop area, production, and irrigated area were based on those reported in the various issues of *Yearbook of Agricultural Statistics of Bangladesh* published by the Bangladesh Bureau of Statistics.

- Monthly Et_p data were available for 64 districts from Water Resource Planning Organization (WARPO) and Centre for Environmental Geographical Information System (CEGIS).
- Crop coefficients were available on a decadal (10-day) basis for different varieties of rice (BARC 2001). Median sowing/transplanting and harvesting periods that that this study has used were from BARC (2001).
- Monthly rainfall data were available for 64 districts for four decades. For most districts, the information was available until 2002. The present study extended the series to 2004 by using the median values for the preceding years.
- *Boro* rice was completely irrigated while other rice crops represented a combination of irrigated and rainfed areas.
- Rice crops did not have any separate production and yield data of the rainfed and irrigated ecosystems on a time series basis. The only data available to the authors were from FCPO (1991). These have been used to derive separate crop production estimates data. While this was not entirely satisfactory, the authors had little choice but to use them while acknowledging their limitations.

The ET_p, and monthly rainfall data which are available for 64 (smaller districts) are reduced to the 21-district level in order to conform to the crop production and related data by averaging the information for the component districts as set out in Table 1A in the appendix.

4. DISTRICT-LEVEL WATER PRODUCTIVITY: EMPIRICAL RESULTS

Employing the technique and the data discussed above, this section presents the empirical results for the average, and marginal productivities in Bangladeshi rice over the thirty-seven year period. It also discusses growth and changes in water productivity variations across districts and over time.

4.1 District-level Growth in Average Water Productivity

1968-2004

Table 1 presents compound annual growth rates of water productivity for the annual (ANUALGR), kharif (KHARIFGR), and rabi (RABIGR) rice crops. Growth rates are also presented for the GDA and other districts (NGDA). Some patterns can be identified.

- KHARIFGR was much higher than RABIGR. Only three districts experienced kharif growth rates lower than 1.5 per cent per annum.
- RABIGR for Barisal, Patuakhali, Chittagong, and Chittagong Hill Tracts was not statistically significant. No districts experienced annual compound growth rates of 1 per cent while only four districts registered annual growth rates above 0.7 per cent.
- ANUALGR in rice water productivity exceeded 1 per cent only in three districts. In six other districts, it ranged between 0.8 and 1.0 per cent.
- The eight GDA districts as a whole registered higher growth rates than the thirteen NGDA districts taken together for the kharif and annual crops of rice while their combined growth was lower than for the remaining districts for the rabi crop.

At this stage, two important questions arise:

1. To what extent were the seasonal growth rates (KHAIRFGR and RABIGR) related to each other and were they related to ANUALGR in any significant way?

2. To what extent did KHAIRFGR and RABIGR determine ANUALGR?

In answering the first question, the study did not find any statistically significant correlation between the seasonal growth rates (r = 0.179, p<0.439). However, both the seasonal growth rates were significantly positively correlated with ANUALGR (r = 0.683 with KHARIFGR, p<0.001; and r = 0.699 with RABIGR, p<0.001).

The answer to the second question required the estimation of Equation (3):

$$ANUALGR = 0.121 + 0.227*KHARIFGR\ (p<0.0001) + 0.408*RABIGR\ (p<0.0001) \qquad (3)$$

F (2, 18) =38.5 (p<0.0001); Adjusted R^2 = 0.789.

It is clear from the Equation (3) that the seasonal growth rates are significant determinants of the annual growth rate. Furthermore, the coefficient of RABIGR is almost twice as influential as that of KHARIFGR.

INSERT TABLE 1

Sub-period growth rates

The sub-periods defined in this study broadly conform to the following characterization of the green revolution and changes in agricultural policy regimes:

Phase 1 (1968-1980): Early green revolution phase with significant input subsidies;

Phase 2 (1981-1990): Advancing established phase of the green revolution and policy rationalization with greater role of market forces; and

Phase 3 (1991-2004): Matured phase of the green revolution with maximum operation of market forces

This study estimated growth rates in average water productivity for each district for the above sub-periods. These growth rates are not presented here for brevity but their salient features are reported. These growth rates showed wide dispersions between sub-periods. A noteworthy feature is that growth rates of many of the districts were not statistically significant. Furthermore, a district, which recorded significant growth in one sub-period, did not necessarily do so in another sub-period. The remainder of this section is devoted to identifying some patterns.

Phase 1 (1968-1980)

Kharif rice water productivity (KHARIFGR)

About a third of the districts did not register statistically significant growth in this phase. The remaining fourteen districts registered growth rates ranging between 1.57% (Rajshahi) and 8.56% (Patuakhali) with for three other districts (Noakhali, Khulna and Kishoreganj), kharif water productivity growing at rates in exceeding 4%.

Rabi rice water productivity (RABIGR)

Only two of the 20 districts (Bogra and Rajshahi) registered statistically significant positive growth rates while five other districts (Barisal, Jessore, Kushtia, Mymensingh and Patuakhali) displayed retrogression. None of the remaining thirteen districts registered statistically significant growth rates in this period.

Annual rice water productivity (ANUALGR)

Thirteen out of twenty districts achieved statistically significant growth rates during this phase. Of these only two districts (Noakhali and Patuakhali) registered growth rates in excess of one per cent.

Phase 2 (1981-1990)

Kharif

Only eight of the twenty-one districts registered statistically significant growth rates. Two districts (Noakhali and Patukhali) which displayed significant growth in Phase 1 registered significant negative growth in the Phase 2. Growth for Chittagong Hill Tracts, Sylhet and Dinajpur turned from insignificant in Phase 1 to significant in Phase 2 while the opposite happened in case of Pabna, Comilla, Tangail, Dhaka, Kushtia and

Mymensingh. The growth rates of Chittagong, Kishoreganj and Pabna declined from high positive to low positive. The opposite was the case with Bogra and Jessore districts.

Rabi

For nineteen districts, growth rates were not statistically significant. Of the remaining two districts, Jessore's growth rate was positive (negative in Phase 1) while that for Chittagong was negative (insignificant in Phase 1).

Annual

The growth rates of eleven districts turned out to be statistically significant with two districts (Bogra and Jessore) registering higher than 2% growth. Chittagomg Hill Tracts, Kishoreganj, Rangpur and Sylhet made a transition from statistically insignificant to significant growth rates for Chittagong, Comilla, Dhaka, Mymensingh, and Tangail the opposite happened between the first and second phases. Bogra, Dinajpur Jessore Kushtia and Pabna made a transition from lower to higher growth rates during the same period.

Phase 3 (1991-2004)

Kharif

Only nine out of twenty-one districts registered statistically significant growth rates. The growth rates of nine districts (Barisal, Comilla, Dhaka, Jamalpur, Khulna, Kushtia, Mymensingh, Rajshahi and Rangpur) turned from statistically insignificant to significant between the second and third phases. On the other hand, for four districts (Bogra, Dinajpur, Kishoreganj and Noakhali) the growth rates turned from statistically significant to insignificant between the last two phases of the time series. Three districts (Chittagong Hill Tracts, Jessore and Sylhet) displayed registered a decline in growth from high positive to low positive in Phase 3 relative to those in Phase 2.

Rabi

For all but two (Dinajpur and Patuakhali) of the twenty-one districts, growth rates were statistically significant and positive. The growth rates ranged between 0.72% (Rajshahi) and 2.01%(Noakhali).

Annual

Only three districts (Bogra, Chittagong and Noakhali) registered statistically insignificant growth rates. Nine districts made a transition from insignificant to significant growth rates in this phase compared to the previous one. Sixteen districts recorded growth rate in excess of 1% with Jamalpur (1.72%), Mymensingh (1.63%) and Dhaka (1.52%) at the top end of the ladder.

4.2 Marginal Productivity of Water in Rice Production in Different Seasons over Time and Its Growth in Selected Sub-Periods

Table 2 sets out levels in marginal physical productivity (MPP) of water in rice production over time and selected sub-periods. MPP, defined as the rate of change of rice crop output (kilogram) due to an m^3 change in CWU for each year, was obtained by estimating Equation (4):

$$QCROPit = \alpha + \beta_{it} CWUit + \varepsilon. \qquad (4)$$

Where *QCROPit* and *CWUit* respectively represent the crop output and consumptive water use for i^{th} crop of rice across all districts in a given year t. The βs represent MPPs of the relevant rice crop in year t.

The information contained in Table 2 suggests that:

- MPP of kharif rice crop (KHARIFMP) has always been lower that for the rabi (RABIMP) and annual rice (ANUALMP) crops. This is due to the faster pace of adoption and deeper penetration of the HYV technology during the rabi season.
- Of the three phases defined above, the average first phase level KHARIFMP is quite low in absolute terms (289g. per m^3 increase in CWU), which declined in the second phase but increased in the third phase. Relative to the first phase KHARIFMP increased by 38 per cent in the third phase recovering from a 20% decline (to 231g.) in the second phase. Over the entire sample period of thirty-seven years, KHARFMP has remained much the same as that in the first phase.
- RABIMP increased only about 16 per cent in the first phase (from 345g. to 399g.) in the second phase. However, it increased by more than 60 per cent to 556g. in the third phase relative to that in the first phase.
- For the annual crop, MPP (ANUALMP) remained stagnant (at about 300g.) during the first two phases but increased by about 45 percent (to 437g.) in the third phase.

While the above provides a broad picture of the movement of MPPs over time, these measures averaged over a decade or longer do not capture their true time trend. Table 3 presents compound annual growth rates based on semi-logarithmic trend corrected for autocorrelation by the Cochrane-Orcutt method. The following patterns seem to emerge:

- Over the thirty-seven year period, KHARIFMP, RABIMP, and OVERALLMP registered growth rates of about 2%, 0.5% and 0.76% respectively.

- In the first phase (1968-1980), KHARIFMP grew at an annual rate close to 3 per cent, while RABIMP did not experience any statistically significant trend. ANUALMP grew at a statistically significant *albeit* much slower rate of 1.13%.
- In the second phase (1981-1990), growth rate in KAHRIFMP declined to just over 1.7% with RABIMP registering no statistically significant trend. The ANUALMP recorded a slightly higher growth rate compared to the first phase.
- In the third phase (1991-2004) growth rates in all three MPPs picked up quite significantly. RABIMP growth staged the most significant recovery growing nearly at 1% per cent per annum.

INSERT TABLES 2 & 3 ABOUT HERE

In contrast to the lack of significant correlation between seasonal growth rates, the study found a statistically significant correlation between the seasonal MPPs (0.862, $p<0.0001$) over time. Furthermore, both the seasonal MPPs were significantly positively correlated with ANUALMP (r = 0.962 with KHARIFMP, $p<0.0001$; r = 0.945 with RABIMP, $p<0.0001$). As indicated by Equation (4) below both the seasonal MPPs are significant determinants of the ANUALMP. Furthermore, the coefficient of KHARIFMP is numerically substantially more influential than that of RABIMP. This is in contrast to the scenario represented by Equation (3) above.

ANUALMP = - 0.067 + 0.720*KHARIFMP ($p<0.0001$) + 0.470*RABIMP ($p<0.0001$)   (4)

F (2, 34) =760.9 (p<0.0001); Adjusted $R^2 = 0.977$.

4.3 Marginal Productivity of Water in Rice Production for Bangladesh Districts

Table 4 presents MPP of rice across districts using the corresponding output-CWU combination for each district. It was obtained by estimating Equation (5) corrected for auto-correlation using the Cochrane-Orcutt method:

$$QCROPip = \alpha + \beta CWUip + \varepsilon. \quad (5)$$

Where *QCROPip* and *CWUip* respectively represent the crop output ing. and consumptive water use for i^{th} rice crop in all years for the p^{th} district. The βs represent MPPs of the relevant rice crop for the respective districts.

The information presented in Table 4 suggests that the level of:

- KHARIFMP ranged between 156g. (Jamalpur) and 348g. (Comilla). For two thirds of the districts it stood below 300g. The best performing districts were Comilla, Noakhali and Chittagong.
- RABIMP ranged between 397g (Chittagong) and 682g. (Tangail). Five of the twenty-one districts recorded RABIMP level below 500g. (Chittagong, Sylhet, Kishoreganj, Chittanong Hill Tracts, and Patuakhali). In three districts (Tangail, Comilla and Pabna) it exceeded 600g. The remaining thirteen districts RABIMP stood in the 500-600g.
- ANUALMP ranged between 143g. (Jamalpur) and 406g. (Chittagong Hill Tracts). The 'top' performers were Chittagong Hill Tracts (406 g.) Bogra (375g.) and Noakhali (371g.).
- KHARIFMP and ANUALMP were marginally higher in the non-Ganges dependent group of districts relative to those in the Ganges dependent group. The opposite seems to be the case for RABIMP, which is 11 per cent higher for the GDA districts.

On the whole, judged by the coefficients of variation, inter-district MPPs show a greater degree of divergence in case of KHARIFMP and ANUALMP (both around 22.5%)

relative to RABIMP (14%). Furthermore, the study did not find any statistically significant correlation between the seasonal MPPs across districts (r = - 0.237 between KHARIFMP and RABIMP, p<0.300). Furthermore, RABIMP did not bear any significant correlation with ANUALMP (r = - 0.182, p<0.429). However, KHARIFMP was significantly positively correlated with ANUALMP (r = 0.825, p<0.001). It is also clear from the Equation (6) that only KHARIFMP is the significant determinant of ANUALMP.

ANUALMP = 0.048 + 0.932*KHARIFMP (p<0.0001) + 0.013*RABIMP (p<0.918) (6)

F (2, 18) =19.2 (p<0.0001); Adjusted R^2 = 0.641.

The above stands in sharp contrast to the estimated relationships resulting from Equations (3) and (4).

INSERT TABLE 4 ABOUT HERE

5. ANALYSIS AND DISCUSSION OF EMPIRICAL RESULTS: ARE THERE ANY 'HOT SPOTS' AND 'BRIGHT SPOTS' OF WATER PRODUCTIVITY IN BANGALDESH?

In light of the empirical results presented in Section 4, this section provides further analysis with a view to identifying any 'hot spots' and 'bright spots' in rice water productivity. This is based on levels of: (a) average water productivity; and (b) marginal water productivity presented in Table 1 and Table 4 respectively.

As noted earlier, the pace at which average water productivity has grown over time varies across seasons and differentially impact on the growth in annual water productivity (ANUALGR). Levels of MPPs also differ across seasons. Under these circumstances, a uniform dividing line to identify 'hot spots' and 'bright spots' may not be appropriate. Against this background, Table 5 classifies districts as ‘hot spots’ and ‘bright spots’ based on compound annual growth rates reported in Table 1.

INSERT TABLE 5

5.1 Classification Based on Annual Growth Rates in Average Water Productivity

Table 5 classifies districts as ‘hot’ and ‘bright spots’ based on compound annual growth rates reported in Table 1. For the kharif crop, three districts (Jessore, Kushtia and Rajshahi) can be considered as ‘hot spots’ which have experienced annual growth rates in excess of 2.5 per cent. The ‘bright spots’ districts are those that have recorded annual growth rates in the 2-2.5 per cent range. Five districts fall in this category. It can be noted that five (Jessore, Kushtia, Rajshahi, Khulna and Pabna) of the eight districts experiencing the fastest growth in average water productivity were from the Ganges dependent area.

The rabi season scenario is a quite different in that none of the districts has experienced growth rate in excess of 1 per cent. In such a situation, hot and bright spots are defined as those that have registered annual growth rates in excess of 0.75 per cent and in the 0.7-0.75 percent range respectively. Only four districts (Jamalpur, Mymensingh, Kishoreganj and Rajshahi) meet these criteria. Of these four districts, only Rajshahi is from the GDA.

For the annual rice crop, yet another dividing line is applied. The districts that grew at rates faster that 1 per cent were in the hot spot category while those that grew between 0.8 and 1 per cent constituted the bright spots. Note that five of the nine fastest growing districts in annual rice water productivity are from the GDA. Panels A, B and C in

Figure 1 respectively identify the ‘hot spots’ and ‘bright spots’ for kharif, rabi and annual rice crop water productivity growth rates.

INSERT FIGURE 1 ABOUT HERE

5.2 Classification Based on Levels of Marginal Water Productivity

Table 6 classifies ‘hot spots’ and ‘bright spots’ based on levels of marginal water productivities for the kharif, rabi and annual rice crops. Given the differential levels of MPPs of water for different rice crops, a uniform dividing line is not applied.

For KHARIFMP, only two districts (Noakhali and Comilla) emerge as ‘hot spots’ based on a dividing line of 340g. or higher, while five districts can be considered ‘bright spots’ applying a dividing line in the 300-340g. range. Note that only one of these seven top performing districts (Barisal) is from the GDA.

For RABIMP three districts (Tangail, Comilla and Pabna) can be considered as ‘hot spots’ based on a dividing line of 600g. or higher. Eight other districts are classified as ‘bright spots’ using a dividing line in the 550-600g. range. Four (Pabna, Kushtia, Rajshahi and Faridpur) of the eleven districts in these two categories are from the GDA.

For eleven districts, ANUALMP exceeded 300g. with five of them registering above 350g. marginal productivity (‘hot’ spot). There were no ‘hot spots’ from among the GDA districts. Only two (Barisal and Jessore) of six districts in the ‘bright’ spot category belong to the GDA districts.

This is illustrated in Figure 2. Panels A, B and C respectively identify the ‘hot spots’ and ‘bright spots’ for kharif, rabi and annual rice crop marginal water productivity measures.

INSERT TABLE 5

INSERT FIGURE 2 ABOUT HERE

5.3 Observed Pattern: Some Exploratory Explanation

The discussions so far have focused on movement of measures of district-level average and marginal water productivity over time, and across districts. This section sums of the salient features of these changes and provides some exploratory explanation.

Salient features

(1) Significant inter-district variation with no uniform 'hot' or 'bright spots' with rankings varying across seasons and sub-periods.
(2) Relative poor performance in the second sub-period (1981-90).
(3) Relative poor rabi season and better kharif season performance in regions of greater climatic variability and vulnerability to droughts.

Exploratory explanation

Several forces are at work in underpinning the changes catalogued above.

Changes in (1) above may be attributable to differential pace of the spread of new technology primarily the area under high yielding varieties of rice in different seasons. While all districts in general have experienced high rates of growth in the area under HYVs, the non-GDA districts have experienced higher pace than the GDA districts. Furthermore, the higher growth rates in the kharif season average water productivity in the GDA districts is due to small base values as can be seen from Table 7 which presents water productivity levels for 1970 and 2004 for comparative purposes. On the other hand, the GDA districts have relatively higher base values in contrast to the non-GDA districts. This is illustrated in Figure 3. Panels A, B and C illustrate the average water productivity levels for kharif, rabi and annual crops respectively for 1970 and 2004. Note that there a significant positive correlation between kharif and annual water productivities for 1970 and 2004.

Relative poor performance in the second sub-period as mention in (2) is probably due to the policy transition phase in the 1980s from primarily a regulatory policy environment to a greater role of market forces. These changes led to increased prices of vital inputs like fertilizer and irrigation water, which might have affected the pace of productivity change. Furthermore, there might have been an 'adjustment to the policy transition' at work.

INSERT TABLE 7 AND FIGURE 3 ABOUT HERE

The phenomenon stated in (3) is due in the main to the overall quality of the main driver of productivity growth – extraordinary growth in groundwater irrigation throughout the country underpinning the concomitant increase in the of area under HYVs of rice especially during the rabi season. The areas with the highest vulnerability to severity of droughts area located in the three GDA districts (Jessore, Kushtia and Rajshahi, Alauddin and Hossain 2001). The quality of irrigation services depends critically adequacy and timeliness of supply of irrigation water. There is considerable uncertainty of water supply due to the lack of timely supply of co-operant inputs such as diesel and electricity. While power failure and the consequential uncertainty of irrigation water is a common occurrence throughout Bangladesh, its impact is likely to be more severe in drought prone areas than in the areas that are less so. In the GDA districts, there is greater incidence of underground aquifers not being fully recharged (Alauddin and Hossain, p.201). At the other end of the spectrum, availability of irrigation facilities provides an opportunity for supplementary irrigation during kharif season to offset any uncertainty in rainfall. This provides greater certainty water availability in the season, which had hitherto no access to supplementary irrigation.

6 CONCLUDING COMMENTS

This paper has undertaken a spatio-temporal analysis of water productivity. In doing so, it has estimated two measures of water productivity – average and marginal. Overall, there is an upward trend in both measures of water productivity while differing widely among districts and over sub-periods. The paper did not find any evidence of consistent 'hot spots' and 'bright spots' in rice water productivity. They were specific to seasons and sub-periods. This paper represents a departure from a limited but growing literature in its emphasis on time series analysis at a disaggregated (e.g. district) level.

Water productivity is critically dependent on groundwater irrigation especially in areas where water is a highly scarce environmental resource. The increasing water intensity in the production process can be illustrated by Figure 4, which depicts a hypothetical representation of the early 1970s and early 2000s of the patterns of environmental capital intensity (proxied by groundwater usage) of agricultural production in Bangladesh. The horizontal axis measures the environmental capital while man-made capital and human labour including human capital as a composite input is measured along the vertical axis. The flatter ray OD typically represents the current Bangladesh scenario as production is more environment-intensive given the high propensity to treat environment (groundwater) as a non-scarce or abundant factor or worse still as a 'free gift' of nature. The steeper ray OC on the other hand depicts a hypothetical initial environment-intensity of agricultural production. Given the fragility of the physical environment, groundwater resources in Bangladesh need to be valued more highly than at present.

INSERT FIGURE 4 ABOUT HERE

While Bangladesh as a whole in general and the GDA districts in particular has significantly increased rice output, the process has exposed the fragility of the physical environment. This is especially so in the GDA districts where groundwater is at least partially a non-renewable resource. It might be getting worse with increasing water deficit in the coming decades (WARPO 2002, p.13). It is debatable whether the present water productivity growth process is sustainable.

Could there be a case for concentrating on rice production kharif season in GDA and release the pressure on groundwater during the dry season by switching to less water consuming crops? As of 2004, in the GDA districts only 45 per cent of the area is under HYVs of rice in the kharif season compared to 59 per cent in the non-GDA districts. The corresponding figures for rabi HYVs are 98 per cent and 94 per cent respectively. Thus there is significant potential for extending kharif HYV areas in all areas but more so in the GDA districts.

To explore the potential for a switching to less water consuming crops such as legumes, fruits and vegetables away from a more water consuming crop such as rice during the dry season in GDA areas requires an in-depth investigation of water productivities for these crops.

As a first study of its kind, the conclusions need to be considered with caution. Explanation of water productivity differences among districts will require an in-depth analysis involving technological and hydro-climatic factors. This type of analysis forms the basis of a separate study.

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Table1: Compound growth rates (per cent per annum) of average rice water productivity (kg/m^3) by Bangladesh districts, 1968- 2004

Districts	KHARIFGR[b]	RABIGR[b]	ANUALGR[b]
Barisal[a]	1.445	Statistically insignificant	0.434
Bogra	2.124	0.627	0.891
Chittagong Hill Tracts	1.879	Statistically insignificant	0.624
Chittagong	1.954	Statistically insignificant	0.591
Comilla	1.812	0.429	0.785
Dhaka	1.299	0.698	0.761
Dinajpur	1.472	0.345	0.698
Faridpur[a]	1.681	0.659	0.816
Jamalpur	1.622	0.939	0.872
Jessore[a]	3.162	0.467	1.095
Khulna	2.459	0.576	0.757
Kishoreganj	2.026	0.743	0.762
Kushtia[a]	3.077	0.589	1.038
Mymensingh	1.551	0.770	0.748
Noakhali	1.676	0.386	0.615
Pabna[a]	2.430	0.699	1.042
Patuakhali[a]	1.663	Statistically insignificant	0.349
Rajshahi[a]	2.631	0.726	0.966
Rangpur	2.045	0.580	0.869
Sylhet	1.609	0.489	0.499
Tangail	1.941	0.583	0.977
NGDA districts	**1.744**	**0.513**	**0.723**
GDA districts	**2.340**	**0.461**	**0.817**

[a] GDA districts.

[b] Based on semi-logarithmic trend line corrected for auto-correlation using the Cochrane-Orcutt method. Compound growth rates are calculated from the trend line by (i) taking antilog of the slope; (ii) subtracting 1 from it; and (iii) multiplying the difference by 100 (Gujarati 2003, p.180). All growth rates are statistically significant unless otherwise indicated.

Source: Based on data from sources described in Section 3.2.

Table 2: Marginal physical product (MPP) of water in rice production (grams per m^3 increase in CWU), Bangladesh 1968-2004 and selected sub-periods

Year	KHARIFMP	N	RABIMP	N	ANUALMP	N
1968	214	18	343	18	267	18
1969	266	19	357	19	285	19
1970	309	20	363	20	331	20
1971	272	20	303	20	285	20
1972	241	20	313	20	258	20
1973	305	20	320	20	319	20
1974	249	20	312	20	258	20
1975	261	20	328	20	288	20
1976	248	20	400	20	271	20
1977	261	20	334	20	291	20
1978	263	21	272	21	276	21
1979	265	21	351	21	285	21
1980	295	21	381	21	322	21
1981	295	21	368	21	306	21
1982	318	21	373	21	337	21
1983	286	21	386	21	301	21
1984	305	21	395	21	324	21
1985	309	21	347	21	320	21
1986	315	21	370	21	332	21
1987	265	21	387	21	311	21
1988	298	21	405	21	329	21
1989	373	21	400	21	354	21
1990	384	21	415	21	397	21
1991	391	21	432	21	416	21
1992	422	21	433	21	447	21
1993	396	21	439	21	403	21
1994	369	21	428	21	411	21
1995	378	21	453	21	418	21
1996	425	21	474	21	455	21
1997	413	21	506	21	467	21
1998	353	21	522	21	434	21
1999	459	21	536	21	513	21
2000	466	21	560	21	548	21
2001	389	21	550	21	480	21
2002	453	21	563	21	525	21
2003	445	21	578	21	548	21
2004	424	21	607	21	531	21
1968-1980	**289**	**260**	**345**	**260**	**302**	**260**
1981-1990	**231**	**210**	**399**	**210**	**305**	**210**
1991-2004	**399**	**210**	**556**	**210**	**437**	**210**
1968-2004	**285**	**764**	**519**	**764**	**297**	**764**

Notes: MPP for each year was estimated after correcting for heteroscedasticity using robust standard errors. All marginal products are statistically significant unless otherwise indicated.

Source: As in Table 1.

Table 3: Compound growth rates (per cent per annum) in marginal productivity of water in rice production for selected sub-periods.

Period	Compound growth rates (per cent per annum)		
	KHARIFMP[a]	RABIMP[a]	ANUALMP[a]
1968-1980	2.978	Statistically insignificant	0.610
1981-1990	1.734	Statistically insignificant	0.689
1991-2004	2.545	0.957	1.131
1968-2004	1.992	0.497	0.764

[a] Calculated following the same method as described in Table 1. All growth rates are statistically significant unless otherwise indicated.

[b] Not statistically significant.

Table 4: Marginal physical product (MPP) of water in rice production for Bangladesh districts, 1968-2004 (grams per m^3 increase in CWU).

District	KHARIFMP[b]	N	RABIMP[b]	N	ANUALMP[b]	N
Barisal[a]	332	37	518	37	341	37
Bogra	246	37	554	37	375	37
Chittagong Hill Tracts	334	37	435	37	406	37
Chittagong	336	37	397	37	347	37
Comilla	348	37	638	37	366	37
Dhaka	226	37	518	37	256	37
Dinajpur	332	37	591	37	347	37
Faridpur[a]	200	37	574	37	294	37
Jamalpur	156	27	577	27	143	27
Jessore[a]	225	37	513	37	313	37
Khulna	232	37	513	37	244	37
Kishoreganj	298	37	432	37	358	37
Kushtia[a]	216	37	594	37	297	37
Mymensingh	224	37	554	37	251	37
Noakhali	340	37	573	37	371	37
Pabna[a]	249	37	627	37	261	36
Patuakhali[a]	171	36	479	36	186	36
Rajshahi[a]	261	37	582	37	275	37
Rangpur	233	37	592	37	231	37
Sylhet	326	37	428	37	330	37
Tangail	254	35	682	35	326	35
NGDA districts	297	469	507	469	307	469
GDA districts	265	295	561	295	283	295

[a] GDA districts.

[b] Estimated using time series data for each district and have been corrected for auto-correlation using the Cochrane-Orcutt method. All marginal products are statistically significant unless otherwise indicated.

Table 5: ‘Hot spots’ and ‘bright spots’ in average rice water productivity growth by season

KHARIFGR		RABIGR		ANUALGR	
Hot spot (≥2.5%)	Bright spot (2.0-2.5%)	Hot spot (≥0.75%)	Bright spot (0.7-0.75%)	Hot spot (≥1.0%)	Bright spot (0.8-1.0%)
Jessore* Kushtia* Rajshahi*	Khulna* Pabna* Bogra Rangpur Kishoreganj	Jamalpur Mymensingh	Kishoreganj Rajshahi*	Jessore* Pabna* Kushtia*	Tangail Rajshahi* Bogra Jamalpur Rangpur Faridpur*

*GDA districts.
Source: Based on Table 1

Table 6: ‘Hots spots’ and ‘bright spots’ in marginal rice water productivity by season

KHARIFMP		RABIMP		ANUALMP	
Hot spot (≥ 340g.)	Bright spot (300-340g.)	Hot spot (≥600g.)	Bright spot (550-600g.)	Hot spot (≥ 350g.)	Bright spot (300-350g.)
Comilla Noakhali	Chittagong Chittagong Hill Tracts Dinajpur Barisal* Sylhet	Tangail Comilla Pabna*	Kushtia* Rangpur Dinajpur Rajshahi* Jamalpur Faridpur* Noakhali Bogra Mymensingh	Chittagong Hill Tracts Bogra Noakhali Comilla Kishoreganj	Dinajpur Chittagong Barisal* Sylhet Tangail Jessore*

*GDA districts.

Source: Based on Table 4

Table 7: Average water productivity (grams per m^3 of CWU), Bangladesh Districts, 1970 and 2004

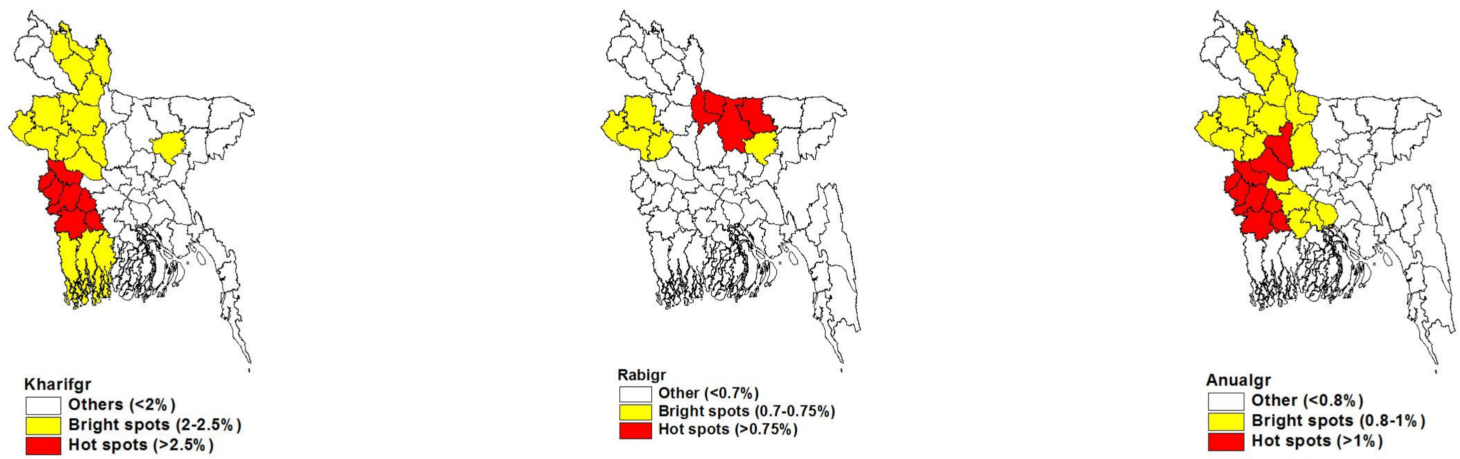
District	Kharif crop		Rabi crop		Annual crop	
	1970	**2004**	**1970**	**2004**	**1970**	**2004**
Barisal*	176	368	568	576	218	409
Faridpur*	177	257	486	706	193	467
Jessore*	206	557	483	588	214	575
Khulna*	187	505	334	495	199	502
Kushtia*	214	504	386	606	216	550
Pabna*	191	408	455	665	202	555
Patuakhali*	128	371	552	365	162	371
Rajshahi*	287	497	347	602	292	553
Bogra	289	493	405	598	295	557
Chittagong	302	602	527	499	356	568
Chittagong HT	271	578	389	492	293	556
Comilla	282	425	463	656	308	567
Dhaka	229	373	402	664	262	556
Dinajpur	291	437	330	655	292	526
Jamalpur[a]	279	446	363	621	288	542
Kishoreganj	230	475	356	650	284	586
Mymensingh	238	476	424	627	256	545
Noakhali	222	360	590	637	244	440
Rangpur	306	452	392	624	308	530
Sylhet	318	436	365	517	334	477
Tangail	182	387	480	736	219	580

*Ganges dependent area

[a] 1980 for Jamalpur

Table 1A: Greater districts (21) and their respective constituent units (64)

Greater Districts (21)	**Component Districts (64)**
BARISAL	Barisal, Bhola, Jhalokathi, and Pirojpur
BOGRA	Bogra, and Joypurhat
CHITTAGONG	Chittagong, and Cox's Bazaar
CHITTAGONG HT	Bandarban, Khagrachhari, and Rangamati
COMILLA	Brahmanbaria, Chandpur, and Comilla
DHAKA	Dhaka, Gazipur, Manikganj, Munshiganj, Narayanganj, and Narshingdi
DINAJPUR	Dinajpur, Panchagarh, and Thakurgaon
FARIDPUR	Faridpur, Gopalganj, Madaripur, Rajbari and Shariatpur
JAMALPUR	Jamalpur, Sherpur
JESSORE	Jessore, Jhenaidah, Magura, and Narail
KHULNA	Bagerhat, Khulna, and Sahtkhira
KISHOREGANJ	Kishoreganj
KUSHTIA	Chuadanga, Kushtia, and Meherpur.
MYMENSINGH	Mymensingh, and Netrokona
NOAKHALI	Feni, Lakshmipur, and Noakhali
PABNA	Pabna, and Sirajganj,
PATUAKHALI	Borguna, and Patuakhali
RAJSHAHI	Naogaon, Natore, Nawabganj, and Rajshahi.
RANGPUR	Gaibandha, Kurigram, Lalmonirhat, Nilphamari, and Rangpur
SYLHET	Habiganj, Maulvibazar, Sunamganj and Sylhet
TANGAIL	Tangail

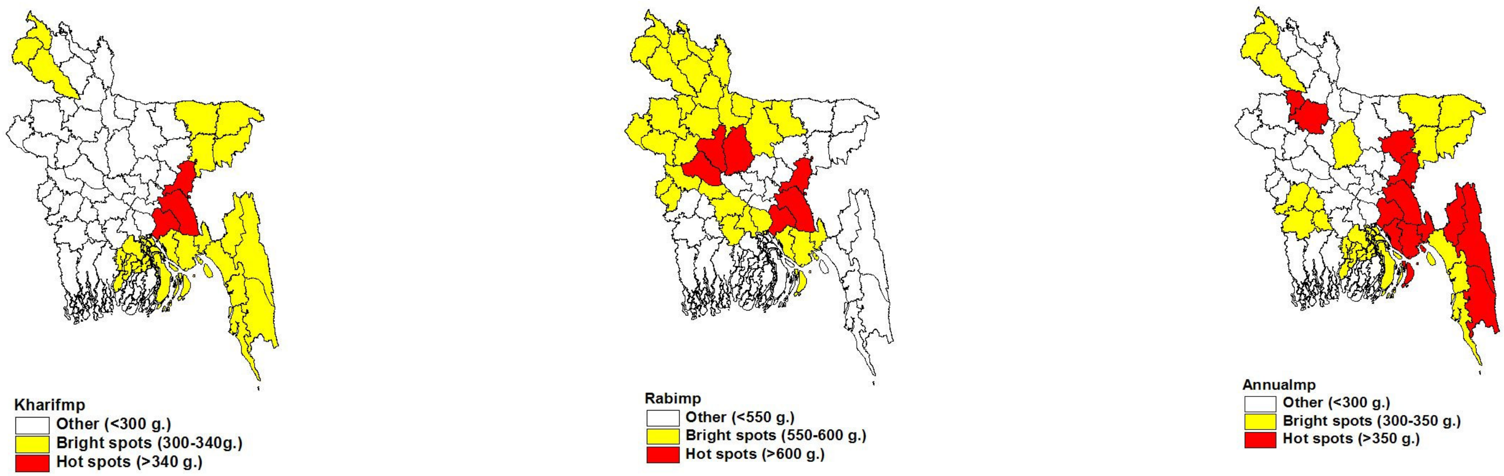


A. Growth rates in average water productivity of kharif rice crop.

B. Growth rates in average water productivity of rabi rice crop

C. Growth rates in average water productivity of annual rice crop

Figure 1: ‘Hot spots’ and ‘bright spots’ of growth in kharif, rabi and annul rice crop average water productivity. (Source: Based on Table 1 and Table 5).

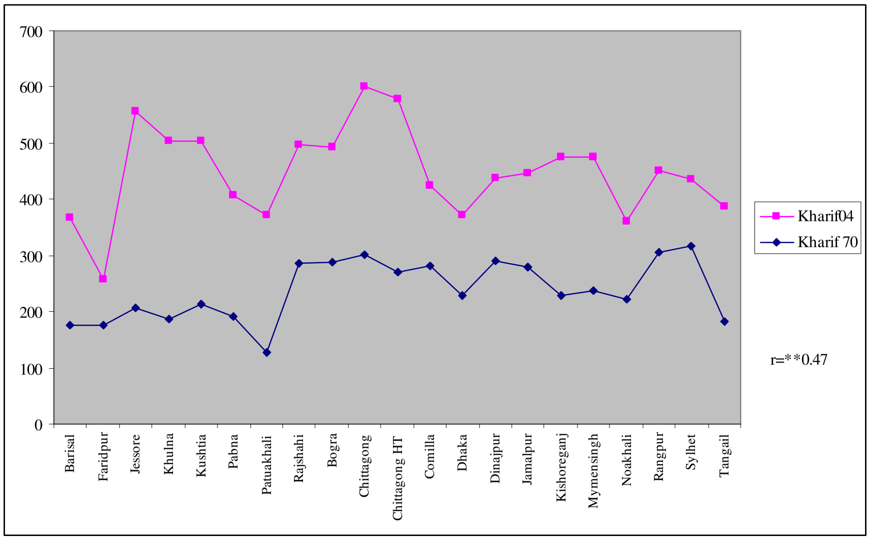


A. Levels of marginal water productivity of kharif rice crop.

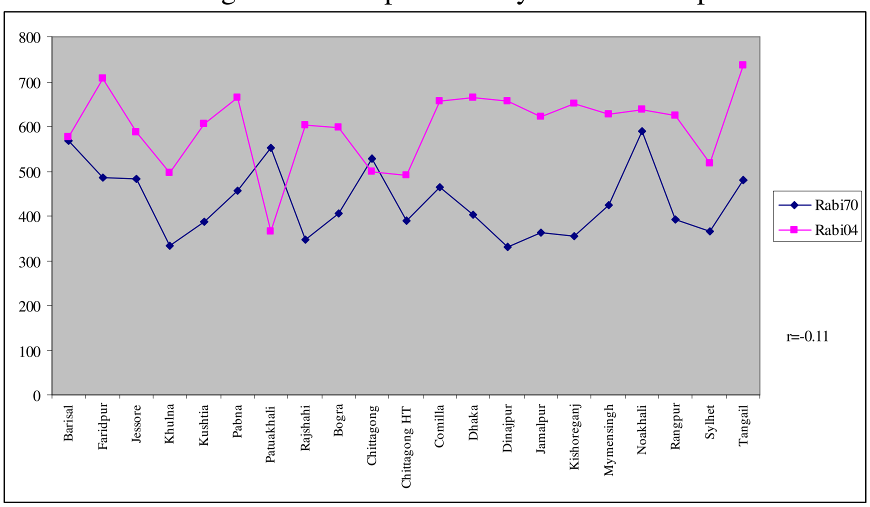
B. Levels of marginal water productivity of rabi rice crop

C. Levels of marginal water productivity of annual rice crop

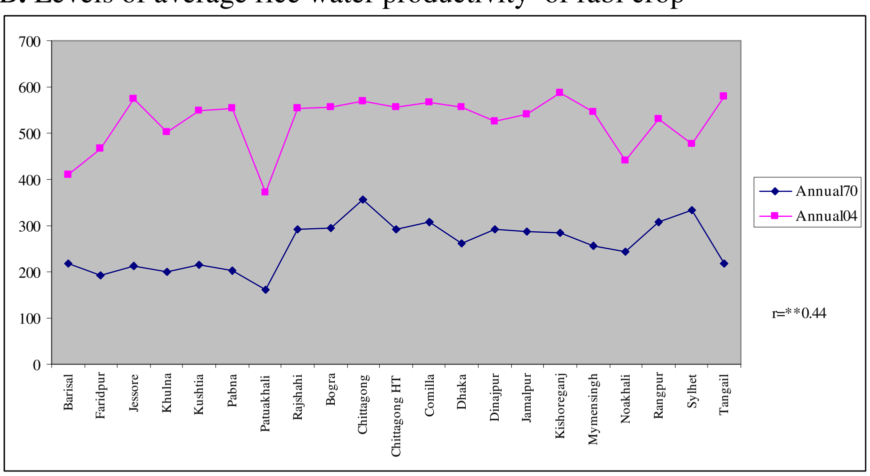
Figure 2: ‘Hot spots’ and ‘bright spots’ of levels of kharif, rabi and annul rice crop marginal water productivity. (Source: Based on Table 4 and Table 6).



A. Levels of average rice water productivity of kharif crop



B. Levels of average rice water productivity of rabi crop



C. Levels of average rice water productivity of annual crop

Figure 3:Levels of average rice water productivity of kharif, rabi and annual crops.