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Full length article

Four decades of rice water productivity in Bangladesh: A spatio-temporal analysis of district level panel data

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ABSTRACT

The bulk of the water productivity (WP) literature has focused on static cross-sectional analysis with inadequate attention given to long-term, time series analysis, either at the country level or at a lower level of aggregation (e.g., district). The present study fills this gap by analyzing WP in Bangladesh using panel data of 21 districts over 37 years (1968–2004) divided into three phases. It estimated levels of, and trends in, WPs of one irrigated rice (*rabi*) crop, and two mainly rain-fed (*kharif*) rice crops, with occasional supplementary irrigation. Also examined were WPs for rice crops in irrigated and rain-fed ecosystems.

The findings indicated that WP levels in Bangladesh were significantly lower than that by global standards. Overall, WP growth rates varied significantly among districts and between phases with no consistent pattern emerging. On the whole, WPs trended upwards while differing widely among districts and between phases, seasons, ecosystems and areas differentiated by physiographic characteristics. The 1980s represented a period of stagnation. Drought-prone areas grew faster while salinity-prone areas grew slower *vis-à-vis* non-drought and non-saline areas. In the Ganges-dependent area, WP grew faster than that in the non-Ganges-dependent area. Rice production in Bangladesh represented a highly groundwater-dependent and fossil fuel-using process with significant environmental implications suggesting that WP growth may be unsustainable. Sustaining WP growth required a range of market and non-market-based policy options.

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1. Introduction

Water is the critical input in the process of intensification of agriculture in densely populated parts of the world, especially South Asia (Shah, 2009; Shah et al., 2003) over the last half century. Given that water could be a limiting factor for crop production and, therefore, food security, measuring water productivity (WP) assumes critical importance. It is surprising then that the literature on agricultural development has focused extensively on land productivity (see e.g., Hayami and Ruttan, 1985) or total factor productivity (see e.g., Heady et al., 2010; Rahman and Salim, 2013) and there has been contrastingly inadequate attention paid to measuring agricultural WP. Molden (2007, pp. 11–12) differentiated between physical and economic water scarcity. The former refers to inadequate investment in water or a shortage of human capacity

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to satisfy demand for water while the latter is primarily due to insufficient water supplies to meet all demands, including environmental flows.

The South Asian country of Bangladesh suffers particularly from significant water resource and production issues which are predicted to grow steadily worse (WARPO, 2002) with an associated dearth of empirical research to help address the problems. While Bangladesh's water scarcity is primarily economic in nature, some parts, such as Nawabganj (#13), Naogaon (#11) and Rajshahi (#12) in the northwest may be approaching physical water scarcity. Furthermore, the quality of groundwater contaminated with arsenic is a critical issue in many parts of Bangladesh and the adjoining areas of the Indian state of West Bengal (Chakraborti et al., 2002). De Vries et al. (2008, p. 1) found that reduction in water quality due to pollution, water-borne diseases and disease vectors was a major concern related to environmental degradation.

The focus of agricultural development in Bangladesh has shifted from a process of external (extensive margin) to internal (intensive margin) land augmentation (Hayami and Ruttan, 1985). The overall process seems consistent with Boserup's (Boserup, 1965; 1981) views that (1) rising population pressure led to the intensification of farming methods in order to increase food production to support extra population; (2) the pressure to change agricultural output by modifying farming techniques was primarily demand-driven.

A range of innovations collectively referred to as the green revolution led to agricultural intensification. The high yielding varieties (HYVs) of rice and wheat in South Asia spread to areas with pre-existing and well-developed irrigation infrastructure primarily dependent on surface water (Raj, 1970). However, subsequent diffusion of the HYV technology became increasingly dependent on groundwater irrigation (Alauddin and Quiggin, 2008; Alauddin and Sharma, 2013) relative to other parts of the world, such as China (Shah, 2007). Groundwater as a source of irrigation has covered nearly 75% of the total irrigated area in Bangladesh in recent years compared to minimal coverage at the beginning of the green revolution in the late 1960s (Alauddin and Tisdell, 1991; Alauddin and Tisdell, 1995; BBS, 2012). Private initiative, small irrigation systems based on low-lift pumps (surface water), and shallow and deep tube wells (groundwater) drawn from streams and groundwater have proliferated. After initial rapid growth, low-lift pump irrigation has slowed significantly since the 1990s due to limited access to reliable surface water sources. This has led to the development of groundwater structures in places previously served by surface water (WARPO, 2002, p. 11).

However, this average percentage of groundwater usage for Bangladesh as a whole has masked significant inter-district variations. For example, usage ranged from more than 95% in the northern districts of Bogra (#8 and #9) and Dinajpur (#1–3), and the central district of Tangail (#37) to minimal or none in the southern districts of Barisal (#24, #28–30) and Patuakhali (#31, 32) (Table 1 and Fig. 1). Furthermore, around 80% of the gross area irrigated in Bangladesh was allocated to rice.

Of particular importance is the focus on the relative performance of the eight (greater) districts (Barisal, Faridpur, Jessore, Khulna, Kushtia, Pabna, Patuakhali and Rajshahi) that constitute the Ganges-dependent area (GDA) accounting for more than a third of Bangladesh's net cropped area (NCA, Fig. 1 and Table 1) *vis-à-vis* the non-Ganges-dependent area (NGDA). This research is part of the International Water Management Institute-Indo-Gangetic Basin (IWMI-IGB) project, and analysis of WP levels and trends was an integral part of this project.

The driest and most severe drought-prone districts are located in the GDA (BBS, 1999). 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 (deficit of rainfall over evapotranspiration) is expected to rise to 445 mm from 343 mm in 2000 and 372 mm in 2025. The wet season (June–October) water surplus (surplus of rainfall over evapotranspiration) is expected to increase to 1221 mm in 2050 from 980 mm in 2000 and 1072 mm in 2025 (WARPO, 2002, p. 13).

Although some drought and salinity-prone districts lie outside the GDA (Table 1), the most severe salinity-prone areas, as with most drought-prone areas, are located in this area. This paper is organized as follows: Section 2 provides a brief review of the relevant literature. Section 3 discusses the materials and method used in the study. Section 4 presents the results for the estimated levels of, and trends in, WPs of one irrigated rice (*rabi*) crop, and two mainly rain-fed (*kharif*) rice crops: combination of *aus* (early monsoon) and *aman* (monsoon–late autumn). It also presents levels of and trends in WPs for rice crops in irrigated and rain-fed ecosystems. Results of Pearson correlation between WP in the irrigated ecosystem and overall WP and *kharif* WP are also presented. Implications and policy options are discussed in Section 5 and Section 6 respectively, and Section 7 provides a brief conclusion.

2. Brief review of literature

Molden (1997) represented the first major research on water productivity. Subsequent research (e.g., Ahmad et al., 2004; Barker et al., 2003; Cai and Rosegrant, 2003; Molden et al., 2003); (Molden and Sakthivadivel, 1999) measured water accounts and crop water productivity on different scales. Cai and Sharma (2010) concentrated on the Indo-Gangetic Basin that included parts of Bangladesh, India, Nepal and Pakistan, while Mahajan et al. (2009) and Jalota et al. (2009) focused exclusively on the Indian Punjab. Cai et al. (2011) measured crop water productivity in ten major river basins, including the Indo-Gangetic, Mekong, Nile and Yellow River basins.

The bulk of the literature on crop WP has concentrated on static cross-section analysis and used aggregate data with occasional micro-level evidence (Molden et al., 2007), even though different scenarios were considered between two points in time such as 2000 and 2025 (Cai and Rosegrant, 2003; Rosegrant et al., 2002). Despite this growth in the literature on WP,

Table 1

Twenty-one greater districts with corresponding smaller districts.

Source: Based on Ahmed and Hussain (2009); BBS (2012); drought-prone area map (Disaster Management Bureau, <http://www.dmb.gov.bd/gis>); SRDI (2010) and WARPO (2002).

21 greater districts	% of net cropped area (NCA)	64 smaller districts (constituent units)	Location and other features
BARISAL	5.4	Pirojpur (24), Bhola (28), Jhalokathi (29), Barisal (30)	Ganges dependent; salinity-prone
BOGRA	3.7	Bogra (8), Joypurhat (9)	Drought-prone
CHITTAGONG	3.4	Chittagong (60), Cox's Bazaar (63)	Salinity-prone
CHITTAGONG HILL TRACTS	0.7	Bandarban (64), Khagrachhari (61), Rangamati (62)	
COMILLA	5.7	Brahmanbaria (54), Chandpur (55), Comilla (56)	
DHAKA	5.0	Dhaka (42), Gazipur (41), Manikganj (39), Munshiganj (43), Narayanganj (40), Narshingdi (44)	
DINAJPUR	5.8	Panchagarh (1), Thakurgaon (2), Dinajpur (3)	Drought-prone
FARIDPUR	5.6	Rajbari (45), Shariatpur (46), Faridpur (47), Gopalganj (48), Madaripur (49)	Ganges-dependent
JAMALPUR	2.9	Jamalpur (33), Sherpur (36)	
JESSORE	5.6	Jhenaidah (20), Magura (21), Narail (22), Jessore (23)	Ganges-dependent area; drought-prone
KHULNA	5.0	Sahtkhira (25), Khulna (26), Bagerhat (27)	Ganges-dependent; salinity and drought prone
KISHOREGANJ	4.4	Kishoreganj (35)	
KUSHTIA	2.7	Meherpur (17), Kushtia (18), Chuadanga (19)	Ganges-dependent area; drought prone area
MYMENSINGH	3.8	Netrokona (34), Mymensingh (38)	
NOAKHALI	3.7	Noakhali (57), Feni (58), Lakshmipur (59)	
PABNA	3.9	Sirajganj (14), Pabna (16)	Ganges-dependent
PATUAKHALI	4.3	Borguna (31), Patuakhali (32)	Ganges-dependent; salinity-prone
RAJSHAHI	8.9	Naogaon (11), Rajshahi (12), Nawabganj (13), Natore (15)	Ganges-dependent; drought-prone
RANGPUR	8.0	Gaibandha (10), Kurigram (5), Lalmonirhat (4), Nilphamari (6), Rangpur (7)	
SYLHET	8.6	Sylhet (50), Maulvibazar (51), Sunamganj (52), Habiganj (53)	
TANGAIL	2.9	Tangail (37)	Drought-prone

Note: Numbers in parentheses in the third column represent the location of the constituent units in Fig. 1.

little attention has been given to an analysis involving long-term time series data either at the country or at a disaggregated (e.g., district) level. One limitation from this shortcoming has been the difficulty in identifying inter-temporal movements in WP for a country or regions within it from any of the studies in the existing literature. To rectify this, Alauddin and Sharma (2013) completed a study that was the first to employ spatio-temporal analysis to explore and identify factors underlying inter-district differences in rice water productivity in Bangladesh.

Vaidyanathan and Sivasubramaniyan (2004) examined changes in water demand for crop production for 13 Indian states between 1966–68 and 1991–93 by employing consumptive water-use (CWU). They used mean annual rainfall and ET that masked significant interregional and seasonal variations of rainfall within a state, and growth periods of crops. Amarasinghe et al. (2007) improved the Vaidyanathan and Sivasubramaniyan (2004) assessment of CWU in two important ways. First, they used average monthly rainfall and district-level ET. Second, they used crop coefficients to estimate CWU for India, involving the ratio of potential to actual ET (Pidwirny, 2006) corresponding to the four different periods of crop growth (initial, development, middle and late), and the crop calendar for different crops for four different regions.

This paper marks a departure from previous studies on WP analysis with a focus on time series analysis at country and disaggregated (e.g., district) levels, employing panel data for 21 Bangladeshi districts over a 37 year period, and rice as a case study. The rationale for using rice as an empirical exploration was due to its pre-eminence as a crop in Bangladesh and its share in crop water usage. The present study builds on Alauddin and Sharma (2013) and focuses on WP growth over time for Bangladesh, its districts, and regions classified by special characteristics and ecosystems.

3. Materials and method¹

Data for 21 districts over 37 years (1968–2004) on crop areas, production and irrigated areas were based on those reported in various issues of the *Yearbook of Agricultural Statistics of Bangladesh* published by the Bangladesh Bureau of

¹ This section was adapted from Alauddin and Sharma (2013, pp. 213–214)



Fig. 1. Map of Bangladesh showing the 21 districts with their 64 constituent units.

Source: Adapted from http://bdbccgroup.files.wordpress.com/2011/09/small_administrative_map_of_bangladesh.jpg ; www.aitlbd.net/bangladesh/mapsbd/index.html.

Statistics. Only the three districts of Jamalpur (#33, #36), Patuakhali (#32, #33) and Tangail (#37) provided data for less than the 37-year period (27, 36 and 36 years respectively).

Because separate production and yield data on a time series basis for rice crops in the rain-fed and irrigated ecosystems were not kept, the only data available to the authors were from the Flood Plan Coordination Organization (FPCO, 1991). These have been used to derive separate crop production estimates.

Monthly ET_p data for the 64 smaller districts were procured by the authors from the Water Resource Planning Organization (WARPO, www.warpo.gov.bd) and the Centre for Environmental and Geographical Information Systems

(CEGIS, www.cegisbd.com). Table 1 and Fig. 1 list and illustrate respectively these 64 constituent units and the corresponding 21 greater districts. Monthly rainfall data were available for the 64 constituent units from CEGIS. The information was available for most of the constituent units until 2002. The study extended the series to 2004 by using the median values for the preceding years. The length of the time series was constrained by the availability of data on all the relevant variables up to 2004. Furthermore, crop-related long-term data were only available for 21 greater districts.

Crop coefficients on a decadal (10-day) basis and the median sowing/transplanting and harvesting periods of different crops of rice were available from BARC (2001).

Rabi rice crop was completely irrigated while other rice crops represented a combination of irrigated and rain-fed ecosystems. These have been used to derive separate crop production estimates. The evapotranspiration (ET_p) and monthly rainfall data for the 64 constituent units were reduced to the 21-district level in order to conform to the crop production and related data by averaging the information for the relevant constituent units.

WP measurement involves both scientific and statistical information on water requirements for crops, rainfall, ET_p , irrigation, crop production cycle, crop output and related data.

Eq. (1) is employed to estimate (Amarasinghe et al., 2007):

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

where:

- IRA_{lk} and RFA_{lk} respectively represent the irrigated and rain-fed areas 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;
- 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; and
- $Effrf_j$ is the effective rainfall for the period of the month in which the crop is grown.

Eq. (1) consists of two multipliers:

1. For irrigated crops it is simply the expression involving the second and third summation signs and entails the use of crop $ET_p (=kc_{ki}^l \times ET_{pj})$ on the assumption that irrigation meets the full water requirement of the crops. In reality, however, this may not be the case because irrigation in many water-scarce areas may not meet the full water requirement. In the absence of any dependable information, the authors had no alternative but to assume away irrigated water deficit. This represents the irrigated multiplier (IM).
2. For the rain-fed crops, it is the minimum of (crop $ET_p, Effrf_j$). This is the rain-fed multiplier (RM).

Based on Amarasinghe et al. (2005, p. 9) Eq. (2) estimates effective rainfall as:

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

where $Effrf$ and AMR represent millimeters of effective rainfall and average monthly rainfall respectively. The present study used actual monthly rainfall data (Cf. Amarasinghe (2005); Amarasinghe et al. (2007)).

For a particular crop or a group of crops, WP has been defined as a ratio of crop output to CWU. This paper estimated WP levels for Bangladesh and 21 of her greater districts over the entire duration of the time series and the specified phases within it.

Phase 1 (1968–1980): early phase of the green revolution with significant input subsidies;

Phase 2 (1981–1990): advancing 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.

The compound growth rates are based on a semi-logarithmic trend line corrected for first-order auto-correlation and involved three steps: (a) taking the antilog of the slope; (b) subtracting 1 from it; and (c) multiplying the difference by 100 (Gujarati, 2003, p. 180).

4. Results

The results for the overall rice water productivity levels and trends are first presented (Section 4.1). This is followed by analyses based on crop seasons (Sections 4.2 and 4.3) and ecosystems (Sections 4.4 and 4.5). Particular attention is paid to

Table 2

Levels and compound annual growth rates of overall rice water productivity by Bangladesh districts for selected phases, 1968–2004.

Greater district (constituent units)	WP level (g/m ³ of CWU)				WP growth rate (% per annum)			
	1968–2004	1968–1980	1981–1990	1991–2004	1968–2004	1968–1980	1981–1990	1991–2004
Barisal (24, 28, 29, 30)	306	261	302	350	***1.363	***2.489	−0.495	***3.111
Bogra (8, 9)	412	294	436	505	***2.296	***2.362	***4.558	*0.974
Chittagong Hill Tracts (61, 62, 64)	459	395	440	532	***1.28	***1.906	−0.843	***1.625
Chittagong (60, 63)	422	347	427	489	***1.57	2.150	***2.19	***1.604
Comilla (54, 55, 56)	407	323	384	501	***1.937	**1.927	***2.275	***2.456
Dhaka (39, 40, 41, 42, 43)	367	291	335	459	***2.01	***2.075	0.594	***3.634
Dinajpur (1, 2, 3)	367	286	355	452	***1.913	**1.02	***3.133	***1.542
Faridpur (45, 46, 47, 48, 49)	280	193	251	381	***2.847	0.351	**3.603	***3.892
Jamalpur (33, 36)	371	290	329	418	***2.172	−1.194	0.871	***4.234
Jessore (20, 21, 22, 23)	358	234	329	494	***3.199	***2.011	***6.341	***2.679
Khulna (25, 26, 27)	344	258	333	432	***2.284	***3.445	1.005	***2.395
Kishoreganj (35)	400	316	381	491	***1.912	*1.4	*1.493	***2.81
Kushtia (17, 18, 19)	326	214	294	452	***3.291	***3.385	**5.03	***3.057
Mymensingh (34, 38)	362	290	341	445	***1.955	***3.058	0.838	***3.81
Noakhali (57, 58, 59)	357	299	334	428	***1.742	***5.297	−1.041	***2.324
Pabna (14, 16)	335	219	308	463	***3.183	***1.992	***3.76	***3.323
Patuakhali (31, 32)	297	267	279	336	***1.25	***5.586	***−2.469	***2.309
Rajshahi (11, 12, 13, 15)	358	252	316	486	***2.707	*1.41	0.881	***2.266
Rangpur (4, 5, 6, 7, 10)	381	280	361	489	***2.307	0.768	***2.476	***2.087
Sylhet (50, 51, 52, 53)	342	295	305	412	***1.428	−0.417	***1.168	***2.945
Tangail (37)	378	275	348	481	***2.55	***3.077	1.779	***3.057
NGDA	381	305	361	460	***1.828	***2.04	***1.201	***2.525
GDA	329	233	305	437	***2.694	***2.15	***2.849	***2.959
Non-drought	363	291	341	442	***1.898	***2.05	*1.015	***2.866
Drought-prone	363	259	344	472	***2.609	***2.385	***3.228	***2.279
Non-salinity	362	275	340	454	***2.225	***2.098	***2.061	***2.719
Salinity-prone	370	305	358	438	***1.641	***2.611	−0.114	***2.375
BANGLADESH	363	280	342	452	***2.137	***2.162	***1.747	***2.67

* $p < .05$; ** $p < .01$; *** $p < .001$. Calculation of compound growth rates is described in Section 2.

differences in the performance of areas susceptible to drought, salinity, and the Ganges and non-Ganges-dependent areas (GDA and NGDA) in all cases.

4.1. Overall rice water productivity

Table 2 presents WP levels and its compound rates of growth for the entire time series, and the relevant phases, and geographical entities. For Bangladesh as a whole, a WP of 361 g/m³ of CWU for the 1968–2004 period or 452 g during 1991–2004 were significantly lower than global standards, ranging between 600 and 1600 g (Zwart and Bastiaanssen, 2004) and 740 g reported by Cai and Sharma (2010) for the different areas of the Indo-Gangetic Basin (see also Cai et al. (2011)).

While differing widely among the districts, the WP levels for Bangladesh as a whole increased by 22% (from 280 to 342 g) between 1968–1980 and 1981–1990, and by 35% (from 342 to 453 g) between 1981–1990 and 1991–2004. The corresponding figures for the 13 districts in the NGDA were 18% (from 305 g to 361 g) and 27% (from 361 g to 460 g). For GDA it increased by 31% (from 233 g to 305 g) and 43% (from 305 g to 437 g) respectively. For the drought-prone areas, the WP level during 1968–1980 was 11% below the non-drought areas (259 g and 291 g respectively). However, it reached comparable non-drought levels during 1981–1990 and exceeded the non-drought area WP by 6.8% during 1991–2004 (472 g and 442 g respectively). The reverse was the case with salinity-prone areas. The WP level in salinity-prone areas was higher during 1968–1980 (305 g and 275 g) and 1981–1990 (358 g and 340 g) but fell below that of the areas unaffected by salinity during 1991–2004 (438 g and 454 g respectively).

The WP levels appeared to be converging over time across regions. For example, the WP level for Bangladesh was 20% higher than that for the GDA (279 g and 233 g respectively) during 1968–1980. This difference declined to 11% (339 g and 305 g) and 4% (453 g and 437 g) for 1981–1990 and 1991–2004 respectively. The divergence between the WP levels between the NGDA and the GDA decreased from 31% (305 g and 233 g) during 1968–1980 to 18% (361 g and 305 g) and 5% (460 g and 437 g) during 1981–1990 and 1991–2004 respectively.

Over the entire time series the WP for Bangladesh grew at a compound annual rate of 2.14% compared with 2.61% and 1.83% respectively for the GDA and NGDA. In all the phases, WP in the GDA grew at a faster pace than in the NGDA and for Bangladesh as a whole. The growth rates in Phase 2 were the lowest of the three phases and the 1991–2004 period recorded the highest rates of growth for Bangladesh as a whole, the GDA and the NGDA.

For the 1968–2004 period and 1991–2004 all districts recorded statistically significant positive growth rates in overall rice WP. Growth rates were not statistically significant in Phase 1 for five districts (Chittagong #60, 63; Faridpur #45–49;

Table 3Levels and compound annual growth rates of average rice water productivity of *kharif* crop by Bangladesh districts for selected phases, 1968–2004.

Greater district (constituent units)	WP level (g/m ³ of CWU)				WP growth rate (% per annum)			
	1968–2004	1968–1980	1981–1990	1991–2004	1968–2004	1968–1980	1981–1990	1991–2004
Barisal (24, 28, 29, 30)	287	241	290	327	***1.435	***3.248	–0.540	***2.837
Bogra (8, 9)	387	287	383	482	***2.149	***2.234	***3.228	0.483
Chittagong Hill Tracts (61, 62, 64)	470	371	446	578	***1.941	***3.641	0.367	**1.425
Chittagong (60, 63)	423	338	421	505	***1.879	2.757	***3.067	***1.716
Comilla (54, 55, 56)	358	289	337	438	***1.81	**1.88	2.174	***1.994
Dhaka (39, 40, 41, 42, 43)	293	258	271	340	***1.29	***2.534	–1.173	***3.898
Dinajpur (1, 2, 3)	346	284	345	406	***1.479	**1.02	***2.856	0.707
Faridpur (45, 46, 47, 48, 49)	216	178	196	267	***1.684	0.438	0.825	**2.011
Jamalpur (33, 36)	320	286	288	350	***1.622	***2.584	–0.379	***4.532
Jessore (20, 21, 22, 23)	347	230	307	485	***3.206	***2.19	***6.181	***2.879
Khulna (25, 26, 27)	343	252	332	435	***2.445	***4.603	0.981	***2.364
Kishoreganj (35)	348	278	334	423	***2.004	***4.162	***2.391	***2.788
Kushtia (17, 18, 19)	314	212	287	427	***3.076	***3.494	*4.725	***2.283
Mymensingh (34, 38)	331	284	322	380	***1.447	***4.097	–0.177	***3.705
Noakhali (57, 58, 59)	328	280	304	389	***1.63	***6.063	***–2.236	**1.869
Pabna (14, 16)	275	207	237	366	***2.461	***2.228	1.394	***3.773
Patuakhali (31, 32)	290	249	279	333	***1.641	***8.045	***–2.434	***2.429
Rajshahi (11, 12, 13, 15)	336	241	299	450	***2.619	*1.588	1.703	***2.517
Rangpur (4, 5, 6, 7, 10S)	362	276	342	456	***2.045	0.771	**2.029	*1.495
Sylhet (50, 51, 52, 53)	339	284	306	414	***1.608	0.680	***2.327	***1.963
Tangail (37)	293	245	248	362	***1.888	***3.081	1.209	***2.239
NGDA	350	287	330	418	***1.694	***2.829	0.929	***2.225
GDA	302	223	278	394	***2.416	***2.534	**2.158	***2.665
Non-drought	332	272	312	398	***1.729	***2.941	0.531	***2.598
Drought-prone	338	250	314	435	***2.4	***2.529	***2.968	***1.921
Non-salinity	328	261	306	404	***1.961	***2.636	***1.516	***2.399
Salinity-prone	366	288	356	446	***1.939	***3.829	0.267	**2.207
BANGLADESH	334	265	313	410	***1.954	***2.802	***1.337	***2.372

* $p < .05$; ** $p < .01$; *** $p < .001$. Calculation of compound growth rates is described in Section 2.

Jamalpur #33, 36; Rangpur #4–7, 10; and Sylhet #50–53) with over 28% of Bangladesh's NCA. In contrast, nine districts with nearly 36% of the country NCA did not experience any statistically significant growth in annual WP during 1981–1990.

4.2. *Kharif* rice water productivity

Table 3 presents the WP levels and the compound rates of growth for the *kharif* rice crop. For Bangladesh, a *kharif* WP of 330 g/m³ of CWU for the 1968–2004 period or 407 g during 1991–2004 was lower than those reported earlier for the overall crop. This applied to other phases and the 1968–2004 period. Significant inter-district variations in levels were observed. In all periods, the *kharif* WP levels for the GDA were below the country average and even more so for the corresponding figures for the NGDA.

The *kharif* WP levels for Bangladesh increased by 18% (from 265 to 313 g) between 1968–1980 and 1981–1990, and by 32% (from 313 to 410 g) between 1981–1990 and 1991–2004. The corresponding figures for the NGDA were similar, at 15% (from 287 g to 330 g) and 27% (from 330 g to 418 g) respectively. The GDA recorded changes of 25% (from 223 g to 278 g) and 42% (from 278 g to 394 g) respectively; *kharif* WP levels appeared to converge over time in a similar manner to the overall rice WP (Table 2).

The picture for non-drought and drought-prone areas was similar to the one for overall rice WP presented earlier in Table 2. However, it was somewhat different for the non-salinity and salinity-prone areas. During 1991–2004, salinity-prone areas as a whole registered a lower level of WP for *kharif* rice than the areas not affected by salinity.

Over the 1968–2004 period, *kharif* rice WP for Bangladesh grew at a compound annual rate of 1.95%, compared to 2.42% and 1.69% for the GDA and NGDA respectively. During 1968–1980, *kharif* rice WP in the NGDA grew at a faster pace than in the GDA and for Bangladesh. In the 1981–1990 period, neither the GDA nor the NGDA registered statistically significant growth rate. During 1991–2004 the GDA experienced higher WP growth rate than the NGDA and Bangladesh combined. The drought-prone areas registered growth rates in the GDA of 2.42%, 2.53% and 2.67% during 1968–2004, 1968–1980 and 1991–2004 respectively in contrast to the NGDA and combined Bangladesh growth rates of 1.73%, 2.94% and 2.60% respectively.

Growth rates for the same saline and non-saline areas offered a similar picture. For the entire period, all districts recorded statistically significant positive growth rates in *kharif* WP. For the 1991–2004 period, all but two districts (Bogra #8–9, and Dinajpur #1–3 with 9.5% of Bangladesh's NCA) registered significantly positive growth rates. The growth rates were not statistically significant during 1968–1980 for four districts, representing just over a quarter of Bangladesh's NCA. In contrast, 11 districts with approximately half the country's NCA did not experience statistically significant growth during 1981–1990.

Table 4Levels and compound annual growth rates of average rice water productivity of *rabi* crop by Bangladesh districts for selected phases, 1968–2004.

Greater district (constituent units)	WP level (g/m ³ of CWU)				WP growth rate (% per annum)			
	1968–2004	1968–1980	1981–1990	1991–2004	1968–2004	1968–1980	1981–1990	1991–2004
Barisal (24, 28, 29, 30)	471	476	425	498	0.195	***−2.905	−0.065	***2.387
Bogra (8, 9)	481	387	545	522	***1.407	***3.348	1.871	*1.265
Chittagong Hill Tracts (61, 62, 64)	451	459	431	458	−0.009	−0.959	***−3.579	***1.899
Chittagong (60, 63)	421	390	452	428	***0.448	0.443	−0.814	***2.072
Comilla (54, 55, 56)	522	478	518	566	***0.952	1.500	0.183	***1.986
Dhaka (39, 40, 41, 42, 43)	472	405	455	548	***1.315	0.929	−0.730	***2.841
Dinajpur (1, 2, 3)	509	468	500	553	***0.721	0.205	−0.744	***1.185
Faridpur (45, 46, 47, 48, 49)	516	447	510	585	***1.166	−0.680	0.487	***3.704
Jamalpur (33, 36)	480	322	455	532	***1.904	*9.635	−0.106	***1.901
Jessore (20, 21, 22, 23)	459	403	461	511	***0.963	***−1.91	***1.856	***2.155
Khulna (25, 26, 27)	355	284	348	427	***1.666	−1.049	**1.389	***2.512
Kishoreganj (35)	447	360	438	536	***1.654	0.262	−0.277	***2.619
Kushtia (17, 18, 19)	424	340	427	501	***1.597	***−2.663	***3.609	***3.545
Mymensingh (34, 38)	438	340	412	548	***1.878	***−3.043	*1.833	***2.805
Noakhali (57, 58, 59)	481	466	445	521	**0.534	−1.724	−0.382	***3.403
Pabna (14, 16)	493	395	519	565	***1.42	−0.709	−0.439	***1.983
Patuakhali (31, 32)	382	448	269	407	−0.658	***−4.203	−3.414	**−2.548
Rajshahi (11, 12, 13, 15)	437	356	406	535	***1.573	***2.06	−8.619	***1.336
Rangpur (4, 5, 6, 7, 10)	472	396	476	540	***1.263	−0.769	−0.240	***2.419
Sylhet (50, 51, 52, 53)	344	304	305	409	***1.259	−1.145	−0.957	***4.257
Tangail (37)	570	496	586	616	***0.963	0.684	*−1.181	***2.393
NGDA	462	412	449	513	***0.947	−0.336	−0.621	***2.024
GDA	451	386	442	517	***1.224	**−1.134	−0.323	***2.514
Non-drought	456	411	436	510	***0.913	***−1.037	−0.616	***2.255
Drought-prone	461	388	467	524	***1.303	0.280	−0.332	***2.053
Non-salinity	463	402	454	523	***1.116	−0.412	−0.480	***2.174
Salinity-prone	426	406	401	461	***0.614	−1.642	−0.774	***2.266
BANGLADESH	458	403	447	514	***1.044	*−0.598	−0.522	***2.188

* $p < .05$; ** $p < .01$; *** $p < .001$. Calculation of compound growth rates is described in Section 2.

4.3. *Rabi* rice water productivity

For Bangladesh, a *rabi* WP of 453 g for the 1968–2004 period or 523 g during 1991–2004 were appreciably higher than those for the annual or *kharif* rice crops (Table 4). This applied to the phases and the time series as a whole. In all phases, the *rabi* WP levels for the GDA were below the country average and for the corresponding figures for the NGDA.

The *rabi* WP levels for Bangladesh increased by 15% (from 385 to 444 g) between 1968–1980 and 1981–1990, and by 18% (from 444 to 523 g) between 1981–1990 and 1991–2004. The corresponding figures for the NGDA were 9% (from 412 g to 449 g) and 14% (from 449 g to 513 g). The GDA recorded changes of 15% (from 386 g to 442 g) and 17% (from 442 g to 517 g) respectively. Non-saline area WP levels were consistently above those in salinity-prone areas in all phases. WP levels were quite the opposite for the drought-prone and non-drought areas in all phases except during 1960–1980.

Over the entire time series (1968–2004) the *rabi* WP for Bangladesh grew at a compound annual rate of 1.04% while the GDA recorded a growth rate of 0.91%, with the NGDA showing the highest growth rate of 1.22%. During Phase 1, *rabi* WP in the GDA and for Bangladesh recorded negative rates of growth while the growth in the NGDA was not statistically significant. *Rabi* did not record any statistically significant rates of growth for Bangladesh, the GDA or the NGDA during 1981–1990. Growth rates during 1991–2004 were appreciably higher but when compared to the entire period were not statistically significant. Overall, salinity-prone areas experienced lower WP growth rates for the entire period of 1968–2004 but the reverse was the case for 1991–2004. Drought-prone areas experienced a higher growth rate during the entire period of 1968–2004 but a lower rate for 1991–2004 than the non-saline areas.

During 1968–1980, the growth rates were statistically significant for eight districts. Of these, four districts with 16% NCA experienced negative growth rates. During 1981–1990, statistically significant positive growth rates were found for four districts (17% NCA), while two districts with 3.6% NCA recorded statistically significant negative growth.

This contrasts with the 1991–2004 period during which all districts registered significant positive rates of growth. For the entire period of 1968–2004, all but one district (Patuakhali #32–33, negative growth) experienced significantly positive growth.

4.4. Rice water productivity in the rain-fed ecosystems

Table 5 sets out WP levels and trends for the rain-fed rice crop. The WP level for Bangladesh overall was consistently higher than in the GDA for 1981–1990 and 1991–2004 but lower for the 1968–1980 and the entire period of 1968–2004.

There did not appear to be any significant difference in rain-fed rice WP between drought-prone and non-drought areas during 1968–2004. During 1991–2004 the WP level (413 g) in drought-prone areas was marginally higher than that in the

Table 5

Levels and compound annual growth rates of average rice water productivity of rain-fed crop by Bangladesh districts for selected phases, 1968–2004.

Greater district (constituent units)	WP level (g/m ³ of CWU)				WP growth rate (% per annum)			
	1968–2004	1968–1980	1981–1990	1991–2004	1968–2004	1968–1980	1981–1990	1991–2004
Barisal (24, 28, 29, 30)	286	240	290	325	***1.434	***3.159	–0.564	***2.849
Bogra (8, 9)	382	285	381	472	***2.084	***2.243	***3.313	0.523
Chittagong Hill Tracts (61, 62, 64)	468	370	440	578	***1.954	***3.619	0.508	**1.425
Chittagong (60, 63)	417	337	414	493	***1.79	2.727	***2.979	**1.719
Comilla (54, 55, 56)	357	289	335	435	***1.793	**1.845	2.137	***2.01
Dhaka (39, 40, 41, 42, 43)	288	256	267	332	***1.212	***2.519	–1.356	***3.778
Dinajpur (1, 2, 3)	341	280	344	396	***1.416	**1.003	***2.981	0.484
Faridpur (45, 46, 47, 48, 49)	213	177	194	260	***1.574	0.440	0.682	*1.796
Jamalpur (33, 36)	316	284	284	346	***1.599	***2.602	–0.436	***4.491
Jessore (20, 21, 22, 23)	330	227	291	454	***2.965	***2.051	***5.502	***2.897
Khulna (25, 26, 27)	342	252	331	434	***2.451	***4.59	1.022	***2.37
Kishoreganj (35)	345	272	331	422	***2.072	***3.97	***2.793	***2.756
Kushtia (17, 18, 19)	277	201	257	362	***2.584	***2.946	4.238	***2.026
Mymensingh (34, 38)	329	283	319	379	***1.448	***4.117	–0.135	***3.748
Noakhali (57, 58, 59)	328	280	304	389	***1.631	***6.036	***–2.219	**1.884
Pabna (14, 16)	266	206	233	346	***2.264	***2.199	1.117	***3.662
Patuakhali (31, 32)	288	247	278	332	***1.633	***7.739	***–2.475	***2.399
Rajshahi (11, 12, 13, 15)	321	235	289	423	***2.461	**1.761	1.138	***2.455
Rangpur (4, 5, 6, 7, 10)	360	274	339	455	***2.06	0.737	**2.145	*1.419
Sylhet (50, 51, 52, 53)	337	284	305	410	***1.584	0.732	***2.286	***1.966
Tangail (37)	288	244	245	352	***1.778	***3.049	1.125	***1.952
NGDA	347	285	328	414	***1.667	***2.788	*0.956	***2.176
GDA	291	220	269	372	***2.246	***2.442	*1.857	***2.578
Non-drought	329	271	310	393	***1.697	***2.892	0.518	***2.56
Drought-prone	326	247	305	413	***2.242	***2.457	***2.747	***1.811
Non-salinity	321	258	301	392	***1.874	***2.578	***1.412	***2.326
Salinity-prone	365	287	354	446	***1.945	***3.787	0.320	**2.213
BANGLADESH	328	262	308	400	***1.88	***2.746	**1.255	***2.31

* $p < .05$; ** $p < .01$; *** $p < .001$. Calculation of compound growth rates is described in Section 2.

non-drought areas (393 g), but was not found to be statistically significant. The rain-fed rice WP level in salinity-prone areas was consistently higher than in non-saline areas.

For the 1968–2004 period, all districts recorded statistically significant WP growth rates. Two districts (Dinajpur #1, 2, 3; Bogra #9, 10, 9.5% NCA) did not experience any statistically significant growth in WP during 1991–2004. This contrasts with the 1981–1990 scenario during which twelve districts (52% NCA) did not experience any significant WP growth for the rain-fed rice crop. Four districts (25.6% NCA) did not experience any significant WP growth for the rain-fed rice crop during 1968–1980. GDA recorded higher WP growth rates in all phases except 1968–1980. Salinity-prone areas registered higher growth rates than areas not affected by salinity during 1968–1980 and 1991–2004. In contrast, lower growth rates emerged across the entire period (1968–2004) and during 1981–1990. A similar pattern of WP growth during all phases and the entire period of 1968–2004 was experienced by the drought-prone areas.

4.5. Rice water productivity in the irrigated ecosystems

Table 6 presents rice WP levels and trends for the irrigated ecosystem. The WP level for Bangladesh as a whole was consistently higher than in the GDA for all phases and the entire period of 1968–2004. GDA WP levels were consistently lower than those in the NGDA for until 1990 and during 1968–2004, and leveled with NGDA during 1991–2004. For the non-drought areas, WP levels were higher during the period overall and during 1968–1980 but lower during 1981–1990 and 1991–2004. Non-saline area WP levels were higher than those in the salinity-prone areas in all phases except 1968–1980.

During 1968–2004, all but two districts (Chittagong Hill Tracts #61–62, 64, and Patuakhali, #31–32 with 5% NCA) experienced significant positive growth rates. However, during 1968–1980, 15 districts (70% NCA) did not experience any significant WP growth while three districts (Barisal #24, 28–30; Jessore #20–23; and Mymensingh #34, 38, 15% NCA) registered significant negative growth rates. This contrasts sharply with the 1991–2004 scenario during which all but one district (Chittagong #60, 63) experienced significant positive WP growth. Notably, 18 districts did not record any significant WP during 1981–1990.

For Bangladesh as a whole, the WP grew at 1.16% per annum over the entire period of 1968–2004. In contrast, the growth rate doubled to 2.31% during 1991–2004. Somewhat similar results emerged with growth rates for the geographical entities based on the GDA–NGDA, drought–non-drought, and salinity–non-salinity classifications during the same time periods. During 1991–2004 higher growth rates were observed for GDA and salinity-prone areas. On the other hand, the non-drought-prone areas as a whole experienced a higher growth rate during 1991–2004.

Given Bangladesh's high dependence on groundwater, the data were analyzed to determine the strength of the correlations between WP in the irrigated ecosystem and overall WP and *kharif* WP (given that part of the *kharif* rice crops

Table 6

Levels and compound annual growth rates of average rice water productivity of irrigated crop by Bangladesh districts for selected phases, 1968–2004.

Greater district (constituent units)	WP level (g/m ³ of CWU)				WP growth rate (% per annum)			
	1968–2004	1968–1980	1981–1990	1991–2004	1968–2004	1968–1980	1981–1990	1991–2004
Barisal (24, 28, 29, 30)	449	456	390	485	0.267	***−3.387	−0.155	***2.831
Bogra (8, 9)	482	388	541	528	***1.425	***3.158	2.090	*1.159
Chittagong Hill Tracts (61, 62, 64)	453	459	439	458	−0.008	−0.835	***−3.522	***1.885
Chittagong (60, 63)	448	393	469	485	***0.847	0.601	−0.250	0.851
Comilla (54, 55, 56)	520	476	513	566	***0.959	1.482	0.215	***2.004
Dhaka (39, 40, 41, 42, 43)	468	399	449	544	***1.343	0.923	−0.605	***2.878
Dinajpur (1, 2, 3)	480	423	461	547	***1.084	0.091	0.398	***1.459
Faridpur (45, 46, 47, 48, 49)	503	439	497	567	***1.112	−0.681	0.718	***3.598
Jamalpur (33, 36)	477	330	447	530	***1.908	*8.779	−0.006	***1.978
Jessore (20, 21, 22, 23)	450	370	443	530	***1.455	***−1.723	***3.7	***1.949
Khulna (25, 26, 27)	359	290	351	428	***1.594	−0.627	0.991	***2.511
Kishoreganj (35)	449	363	438	536	***1.633	0.436	−0.224	***2.632
Kushtia (17, 18, 19)	417	322	391	525	***2.087	−0.416	***5.13	***2.497
Mymensingh (34, 38)	441	346	416	548	***1.815	***−2.682	1.614	***2.804
Noakhali (57, 58, 59)	481	465	444	521	***0.542	−1.608	−0.335	***3.397
Pabna (14, 16)	482	381	503	559	***1.539	−0.494	0.270	***2.147
Patuakhali (31, 32)	407	471	283	441	−0.050	−2.528	−2.005	***1.692
Rajshahi (11, 12, 13, 15)	437	351	404	541	***1.72	**1.358	−3.606	***1.304
Rangpur (4, 5, 6, 7, 10S)	473	413	463	536	***1.087	−0.805	0.072	***2.574
Sylhet (50, 51, 52, 53)	347	306	308	414	***1.291	−1.213	−0.798	***4.152
Tangail (37)	562	490	573	611	***0.986	0.751	−1.063	***2.325
NGDA	463	412	446	519	***1.034	−0.171	−0.324	***2.267
GDA	442	373	426	519	***1.395	*−0.862	0.973	***2.403
Non-drought	457	411	433	514	***0.981	**−0.874	−0.365	***2.527
Drought-prone	455	374	452	530	***1.516	0.593	1.055	***1.885
Non-salinity	462	398	447	529	***1.253	−0.163	0.277	***2.296
Salinity-prone	420	402	394	457	***0.615	−1.624	−0.914	***2.408
BANGLADESH	456	398	439	519	***1.162	−0.385	0.106	***2.312

* $p < .05$; ** $p < .01$; *** $p < .001$. Calculation of compound growth rates is described in Section 2.**Table 7**

Bivariate correlation (Pearson) between selected WP measures for different phases and geographical entities, 1968–2004.

Geographical entity	Irrigated rice—all rice WP				Irrigated rice— <i>kharif</i> rice WP			
	1968–2004	1968–1980	1981–1990	1991–2004	1968–2004	1968–1980	1981–1990	1991–2004
All 21-districts	***0.656	***0.217	***0.501	***0.634	***0.417	0.061	0.093	*0.183
NGDA	***0.640	0.180	***0.625	***0.649	***0.369	−0.006	0.180	0.170
GDA	***0.684	−0.096	0.174	***0.624	***0.478	−0.222	−0.240	0.216
Non-drought	***0.566	0.109	***0.332	***0.597	***0.318	−0.033	0.037	0.156
Drought-prone	***0.794	***0.421	***0.711	***0.735	***0.589	0.263	0.187	0.209
Non-salinity	***0.698	*0.190	***0.537	***0.721	***0.471	0.026	0.125	***0.283
Salinity-prone	***0.443	0.328	***0.617	0.256	**0.332	0.187	0.466	0.131

* $p < .05$; ** $p < .01$; *** $p < .001$.

received supplementary irrigation), and the change in these correlations over the time period of the study. Information contained in Table 7 is included as an aid to depict the dynamics of the relationship.

A significant positive correlation was found between the WP for the irrigated ecosystem and the overall WP for the 1968–2004 period. The strength of the relationship varied from moderately positive ($r = 0.443$) for the salinity prone areas to very strongly positive for the drought-prone areas ($r = 0.794$). In all other cases, the coefficients were strongly ranging between 0.566 for the non-drought areas and 0.698 for the non-salinity prone areas. For the 1991–2004 period a similar pattern of relationship existed except for salinity prone areas for which the correlation was not significant. During the 1968–1980 period the relationship was not significant in all cases except weakly positive ($r = 0.217$) for Bangladesh as whole and moderately positive ($r = 0.421$) for drought-prone areas. For the 1981–1990 phase of the time series, all the correlation coefficients were statistically significant for all areas except the GDA. The strength of the relationship varied from weakly positive ($r = 0.332$) to strongly positive ($r = 0.711$) for the drought-prone areas.

For the entire 1968–2004 period, the strength of the relationship between the WP levels of the irrigated ecosystems and *kharif* WP levels varied between positively strong ($r = 0.589$) for the drought-prone areas to weakly positive ($r = 0.332$). During the 1991–2004, the relationship for Bangladesh as a whole was significant but very weak ($r = 0.183$). For the salinity-prone areas, the relationship was positively weak ($r = 0.283$).

On the whole, despite variations across geographical entities, the correlation between WP levels in the irrigated ecosystems and overall WP levels was relatively stronger than the one between the former and *kharif* WP levels. The analysis also found evidence of an emerging relationship between the irrigated ecosystem WP levels and *kharif* WP levels.

The preceding discussion suggests:

- (1) Significant inter-district variations with no consistent pattern of growth in WP. Overall, there was an upward trend in WP which differed widely among districts and across phases, seasons, ecosystems and geographical entities differentiated by physiographic characteristics.
- (2) The poorest performance during the 1981–1990 period represented the advancing established phase of the green revolution and a policy transition from a regulated policy regime to one with a greater role of market forces.
- (3) Relative poor *rabi* and better *kharif* season performances in regions of greater climatic variability and vulnerability to droughts.

The relative poor performance during 1981–1990 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, such as fertilizer and irrigated water that might have affected the pace of WP change. Furthermore, there might have been a process of adjustment to the policy transition at work.

The phenomenon stated in (3) was likely to be mainly due to the overall quality of the principal driver of WP change—the extraordinary expansion in groundwater irrigation throughout the country underpinning the concomitant increase in the area under HYVs of rice, especially during the *rabi* season. The areas with the highest vulnerability to severe droughts are located in the districts of Jessore, Kushtia and Rajshahi in the GDA (Alauddin and Hossain, 2001). The quality of irrigation services depends critically on the adequacy and timeliness of irrigated water.

There is considerable uncertainty about the irrigated water supply due to the lack of timely supply of co-operant inputs, such as diesel fuel, electricity and fertilizer. While power failure and the resultant uncertainty of available irrigated water are common occurrence throughout Bangladesh, its impact is likely to be more severe in the drought-prone areas. In the GDA there was a greater incidence of underground aquifers not being fully recharged (Alauddin and Sharma, 2013). But the availability of irrigation facilities provided an opportunity for supplementary irrigation during the *kharif* season to minimize the effect of uncertainty in rainfall. This provided greater certainty of water availability in the season when the region had hitherto no access to supplementary irrigation.

5. Implications

Water productivity is critically dependent on groundwater irrigation, especially in areas where water is a highly scarce environmental resource. *Rabi* rice for Bangladesh as whole accounts for nearly 60% of the total rice output about 40% of the gross area (BBS, 2012), which is a sharp increase in four decades from the corresponding 1970 figures of 20% and 10% respectively. This has manifested in increasing agricultural intensification and a considerable increase in the ground–surface water usage ratio (Alauddin and Sharma, 2013).

The results of this study raise implications for the degree to which the pattern of water resource use in Bangladeshi crop production found from the results is sustainable in the future. Consideration of these implications requires a brief discussion of the spectrum of views on sustainability and where Bangladesh's pattern of water resource use lies among them.

Following Pearce (1993) and Turner et al. (1994), one could identify a sustainability position along a continuum from very weak to very strong. For the purpose of this study, a focus on the ends of the continuum of weak and strong sustainability will suffice.

Weak sustainability implies a constraint on the resource-using economic activities in order to maintain populations/resource stocks within upper and lower bounds regarded consistent with ecosystem stability and resilience (Turner et al., 1994, p. 268). Thus, as long as other forms of capital are substituted for natural capital, the weaker versions of sustainability are consistent with a declining level of environmental quality and natural resource availability.

A strong sustainability emphasizes: (a) a constant stock of natural resources; (b) a limited degree of substitutability between natural and manmade capital in order to take care of the posterity (Turner et al., 1994).

The spectrum of views on sustainability, and the resource use pattern in the Bangladeshi crop sector seems to suggest that the discourse of agricultural development is pre-eminently environment-using, not environment-saving. The two fundamental environmental resources of Bangladesh, land and water, are under considerable strain from intensification (Alauddin and Hossain, 2001).

In light of the above, it appears that Bangladesh agriculture meets the conditions of the weaker (growth optimism) rather than stronger (greener) end of the sustainability continuum. Growing focus on *boro* rice may meet the present needs but may be unsustainable given the degradation in the quality of two critical inputs in agriculture—land and water, especially groundwater. The process of agricultural intensification has exposed the fragility of the physical environment.

6. Policy options

Given the resource use pattern in general and water use patterns in particular which is the focus of this paper, it is clear that the key policy option is to ensure the best use of the resource that is in short supply (in this case, groundwater in many areas). This seems paradoxical given that Bangladesh is located in a high rainfall zone of the world. This, however, masks the high seasonality in precipitation, with more than 90% occurring in the four monsoonal months between June and October.

Furthermore, there is considerable uncertainty in the arrival of monsoonal rains. As a result, crop production faces the risk of regular bouts of drought and flood of differing severity with significant adverse implications for crop production.

Water-saving can be achieved in several ways embodying two broad strategies that entail (a) a gradual but substantial shift from dry season rice to non-rice crops, such as pulses and vegetables that are less water-consuming, and (b) a reduction in the relative dependence on the *rabi* rice crop and an expansion of the scope of the *kharif* crop.

Despite significant expansion in the rice area under HYV in the dry (*rabi*) season, actual yields are on average 2 tonnes per hectare below the potential. Point (a) above represents a partial reallocation of land from rice to non-rice crops and does not necessarily imply a reduction in rice output in the *rabi* (dry) season. The *rabi* rice output could be maintained at the present level or increased by bridging the gap between potential and actual yields through improved input and resource management. The land released from dry season rice cropping could be allocated to other crops of higher nutritional value but less in water consumption (Afzal et al., 2004, p. 60). Point (b) implies the need for a significant expansion of HYV rice technology in the *kharif* season through: (i) more effective provision of supplementary irrigation to *kharif* HYV areas, and (ii) greater adaptability of HYVs to various environmental conditions.

The above strategies are underpinned, amongst others, by three categories of policy options: market-based, research and development (R & D)-based and institutional support.

Market-based option

In Bangladesh, pricing of material inputs such as fertilizers, pesticides and irrigation equipment and other machinery has been rationalized through policies that evolved in the 1980s and 1990s. This included the removal of subsidies and exchange rate distortions. However, groundwater (a key environmental good) has been considered a 'free' good even though it is becoming increasingly scarce resources in many parts of Bangladesh.

The owners of irrigation machinery, such as deep tube-wells extract underground water for irrigating their own land and charge a fee at commercial rates for irrigating others' land. Pricing per cubic meter of water irrigated or a fee based on engine capacity could be imposed to demonstrate, at least partially, the true value of this environmental resource. The former is difficult to enforce in practice but the latter is relatively easier to implement. An alternative, complementary strategy could be to design incentive mechanisms for innovation of the environment-saving type, for example, water- and energy-saving mechanical innovations.

R & D-based option

Developing rice and non-rice crop varieties that require less water (water-saving) is critically important. Given the importance of rice, Bangladesh, for example, is a virtual rice monoculture, and there is significant reliance on ground-water irrigation during the dry season. This involves developing technologies or providing incentives for a greater usage of surface water for irrigation given its relative abundance in some parts of Bangladesh. This assumes greater significance because rapid urbanization is likely to place considerable strain on groundwater tables for domestic usage water supplies in urban areas.

Of paramount importance is to extend and intensify research efforts toward developing HYVs of non-rice crops, for example, pulses and vegetables, which are financially attractive to farmers and can partially but effectively replace *rabi* rice crop cultivation. These crop varieties must contain multiple attributes involving wider adaptability to temperature variations, higher yields and lower consumptive water usage. This entails process innovations.

Bangladesh has made significant progress in varietal development and grain quality for widespread adoption in a range of agro-ecological zones that are more suited for *rabi* (dry season) than *kharif* (wet season). Challenges remain for the development of drought- and salinity-tolerant varieties, short maturing varieties with lower water requirements, as well as future climate proofed varieties with higher temperature tolerance (for example, wheat). Bangladesh has developed more than 30 varieties of pulses with high yield potentials and adaptability to a range of environmental conditions. However, challenges remain for short maturing varieties between two rice crops, adaptability to stresses caused by variability in weather conditions, such as the severity of winter, and the high incidence of fog, making it financially attractive to farmers relative to other crops, such as maize or *boro* rice.

Institutional support

There are several ways in which uncertainty surrounding cropping pattern changes from rice to non-rice crops in the *rabi* season and increased coverage of the HYVs of rice in the *kharif* season can be managed or minimized.

Input supply and delivery systems involving adequate and timely availability of critical inputs such as fertilizers and irrigation water need to be more efficient. Uncertainty in energy supplies (power and diesel) has been found to have a detrimental effect on crop yields. This also is likely to affect water productivity.

Given the serious consequences of crop failure, especially for the smaller and marginal farmers, the provision for crop insurance is likely to be an important requirement in reducing the risk of crop failure due to natural phenomena, such as droughts and floods of differing severity.

Furthermore, in order to build awareness and sensitization to resource use and conservation, a significant strengthening of the linkages between education and research is a key approach that is likely to achieve water-use efficiency.

The above by no means represents an exhaustive list of options. However, it embodies some of the major options that Bangladesh could pursue in order to sustain land and water productivity.

7. Conclusion

This paper argues that the process of crop production and attendant consumptive water use, especially groundwater meets the conditions (or, 'criteria') of weak sustainability. It is debatable whether the present WP growth process is sustainable. The paper advocates a set of market and non-market-based, policy options which, if taken as a whole, are likely to sustain water productivity.

This research has contributed to the literature in two important ways. First it has departed from the bulk of existing literature that focuses on spatial dimension of WP and used panel data to provide a spatio-temporal perspective. Second, it has and explored issues such as WP trend analysis across districts, regions, seasons, ecosystems and districts in different time phases that have not been addressed before.

One limitation of this paper is that analysis covered only until 2004. This paper focused on rice only, given its importance in Bangladesh agriculture. However, the methodological framework can be easily extended to other crops and data permitting that the time series can be extended to more recent years as well. Furthermore, this analytical framework can be adapted to other countries such as India with a much more diverse hydrological, physiographic and climatic conditions than Bangladesh.

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