Inter-District Rice Water Productivity Differences in Bangladesh

Explanation, Implications and Policy Options

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Abstract

This paper explains inter-district differences in water productivity of kharif, rabi and annual rice crops in Bangladesh. Employing factor analysis, twenty or so variables representing climatic and hydrological conditions, technological diffusion, and agricultural intensification are reduced to three or four factors. These are then combined with other relevant variables such as time trend, district location, and policy transition to explain spatio-temporal variations in rice water productivity using GLS.

Technological diffusion underpinned by a phenomenal increase in groundwater usage consistently outperforms any other factor explaining water productivity differences. Agricultural intensification is significant and substantial only for the rabi crop. Water productivity is consistently lower in the Ganges-dependent districts but more so for the rabi crop. There is a positive time trend in productivity but it is relatively much stronger for the kharif and annual crops. Climatic factors and policy changes to greater reliance on market forces had a significant negative effect on the rabi rice water productivity. On the whole, water productivity typifies an environment and fossil fuel-using process which at best meets conditions of weak sustainability. Bangladesh needs to achieve internal water augmentation to enhance and sustain land and water productivity and adopt a set of market and non-market based policy options that complement one another. Institutional including crop insurance support is crucial.

Key words: Water productivity; agricultural intensification; policy transition; technological diffusion, environment-intensity; internal water augmentation.

JEL classification: O1, Q0, Q2.

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1 INTRODUCTION

The received literature on agricultural development has long neglected the measurement and explanation of productivity of a fundamental and in many cases limiting input, water. This stands in sharp contrast to the voluminous literature relating to land and labor productivity in agriculture. Explaining productivity growth in agriculture has been the subject matter of extensive research. Colin Clark (1940), in his pioneering study *Conditions of Economic Progress*, first examined productivities per unit of land area and per unit of labor over time and across countries.

It has long been recognized that with a growing population and an accompanying decline in the supply of arable land per capita, there is very little prospect for expanding food production by bringing in more land under cultivation. The only way forward is to augment the productivity per hectare of cultivated land. In their influential work, Hayami and Ruttan (1985, 310-11) espoused internal land-augmentation as opposed to external land-augmentation as a way of overcoming severe constraints on the supply of arable land per capita. The former refers to a situation where qualitative improvement in land input takes place for instance through irrigation while the latter refers to a situation where cultivation is based on the extensive margin.

In the densely populated and land-scarce countries of South Asia, internal land augmentation has taken the form of increasing reliance on ground water irrigation which is a booming industry. In no other part of the world, people's livelihoods depend so much on groundwater as it does in South Asia. For example, as Shah (2007) reports, 55-60 and 60-65 per cent of their respective populations in India and Pakistan depend on groundwater for their livelihoods. The corresponding figure for China ranges between 20 and 25 per cent. Over time, Bangladesh has become increasingly dependent on groundwater irrigation for agricultural crop production. From about 3 per cent in the early 1970s groundwater irrigation accounted for nearly 75 per cent of total area irrigated in 2004.

Over the last three decades, there have been significant changes in the policy direction in two important ways: First, the world now pays much more attention than in the past to letting the market forces operate and to the private sector. Second, the depletion and degradation land and water resources seem manifestly clear. This is a global as well as a South Asian phenomenon. Therefore, the focus of technological innovations must shift from just land-augmentation to environment-augmentation (environment-saving) by considering environment as factor of production (Alauddin 2004; Alauddin and Quiggin 2008). More specifically, in the context of this paper, the focus of agricultural development can hardly ignore a water-saving (water-augmenting or 'wateresque') perspective implying a higher crop yield per m^3 of water use.

The existing literature on water productivity is of recent origin. In the last decade, 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). The existing literature on water productivity suffers from two limitations. First, it concentrates primarily on static cross-section analysis. Second, there is little rigorous analysis on why productivities differ among the units constituting the basis of such analysis.

As a precursor to this study, Alauddin et al. (2008) estimated rice water productivity measures employing district-level time series data on agricultural crop production and consumptive water use and identified differing levels and trends in those measures for 21 Bangladesh districts over the 1968-2004 period. The purpose of the present paper is to specifically address the second issue involving an in-depth analysis of the underlying factors that help explain differing levels of water productivity across districts and over time.

It is well known that agricultural activities take place under a complex system of natural, environmental and technological conditions. Various factors such as rainfall, evapotranspiration, and groundwater depth, relative mix of surface and groundwater usage, intensification of agriculture, adoption and diffusion of improved technology involving areas allocated to HYVs of rice crops, crop diversification (or lack of it) could one way or the other impact on the crop productivity. Other factors such as useable recharge and groundwater depth could also be important underlying factors.

Bangladesh agriculture is characterized, amongst other things, by the preeminent position of rice in its cropping pattern. Furthermore, it depends primarily on spread of improved technology involving HYVs of rice and supported by a critical dependence on irrigation especially groundwater irrigation. Bangladesh while enjoys high annual rainfall, the uncertainty and unevenness of its distribution severely limits the effective use of rainfall for crop production. Bangladesh has a prolonged dry season (November-June). There is also a significant unevenness in the regional distribution of rainfall. The increasing dependence on groundwater has impacted on the groundwater table and potential recharge, hence useable recharge. Historically, the western and northwestern districts of Bangladesh are typically low rainfall areas. The dry season evaptranspiration far exceeds the level of precipitation in this season. This implies growing dependence on groundwater irrigation for agricultural activities.

This paper is organized as follows: Section 2 briefly presents the methodological background to water productivity measures. Section 3 provides a broad overview of changes in Bangladesh agriculture. Section 4 discusses methodological issues focusing on factor analysis in deriving a set of composite variables that are used as probable determinants of the underlying patterns. Section 5 presents the empirical results based on econometric analysis of factors underlying productivity differences. Section 6 discusses implications of the findings. Section 7 discusses some policy options. Section 8 concludes the paper.

2. MEASUREMENT OF WATER PRODUCTIVITY

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

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

Where IRA_{lk} and RFA_{lk} respectively represent irrigated and rainfed 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 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. Further details of data sources and underlying assumptions are provided in Alauddin et al (2008).

3 OBSERVED PATTERNS: SOME BROAD INDICATORS

This section presents and discusses some observed patterns in term of broad indicators of changes across districts and over time. For brevity, data on three points in time are presented in Table A1. These are for:

- 1970 which represents the initial phase of the green revolution;
- 1990 that represents a phase which embody significantly matures state of penetration of the green revolution technology;
- 2004 is the latest year for which detailed district-level data are available.

The data presented in Table A1 suggest the following:

- Three measures of agricultural intensification, namely cropping intensity (gross cropped area as a percentage of net cultivated area); net agriculture intensity (net cultivated area as a percentage of total land area) and gross agriculture intensity (gross cultivated area as a percentage of total land area) have registered significant changes. Cropping intensity is the highest in the drought prone regions of the northern and western districts of Bogra, Jessore and Kushtia due primarily to the spread of groundwater irrigation. This is despite the fact that two of these districts (Jessore and

Kushtia) are located in the Ganges-Kobadok project area, which is supposedly a surface-water irrigated region. As expected net agriculture intensity has registered a consistent decline for all districts. Gross agriculture intensity, which is already high but does not show any consistent pattern of change.

- Remarkable changes have taken place in the most important driver of the new technology i.e., area irrigated by groundwater sources. From next to nothing at the beginning of the green revolution, for all districts it is the preeminent source of irrigation. This is especially so for the districts of Bogra, Dinajpur. Jamalpur, Jessore, Kushtia, Mymesningh, Pabna, Rajshahi, Rangpur and Tangail where the groundwater dependency is over 85 per cent of the gross irrigated area. This is a phenomenon, which by implication has drastically shifted the ground-surface water relativities in irrigation from almost nil to in some cases nearly all. Three standout districts are Bogra, Tangail and Dinajpur where groundwater irrigation is respectively 54, 34 and 24 times as important as surface water irrigation.
- Both the crop concentration ratio (measured by gross rice area as a percentage of gross cropped area) and the rice intensity in irrigated area (gross rice area as a percentage of gross area irrigated) show the preeminence of rice in Bangladesh agriculture.
- The principal agent spearheading the green revolution i.e., HYVs of rice has experienced widespread adoption and diffusion. Almost all rabi rice area in 2004 was allocated to HYVs while kharif rice also had a significant component of HYVs for most districts.
- Significant variations exist across districts in terms of average water productivity over time and across seasons. Rabi rice crop had higher water productivity than kharif rice crop because of more dependable source of water for crop irrigation. The levels of

water productivity for almost all districts have progressively increased over time. These come into sharper focus when illustrated in Figure 1.

INSERT FIGURE 1 ABOUT HERE

Table 1 sets out descriptive statistics of water productivity measures by seasons and districts for the 968-2004 period. Rabi water productivity is considerably higher than the one for kharif. Furthermore, kharif rice water productivity is less stable as displayed the coefficients of variation, than that for the rabi season.

Is there any time trend in the coefficients of variation across districts? Figure 2 illustrates the inter-district coefficients of variation for the 1968-2004 period for the kharif, rabi and annual rice crops. The estimated regression did not find any evidence of any time trend for the kharif crop coefficient of variation. However, the rabi and annual crops displayed statistically significant downward trend in their respective coefficients of variation. This implies a convergence of district level water productivity for the rabi and annual crops.

INSERT FIGURE 2 ABOUT HERE

4 IDENTIFYING POSSIBLE DETERMINANTS: FACTOR ANALYSIS

In light of the broad indicators presented in Section 3, and given the objective of the paper, one could think of a range of variables that might represent those from a set of climatic, technological, agricultural intensification, hydrology, and crop diversification. Table 2 provides list of such variables. The characterization may not quite as precise as has been presented in Table 2 and crossovers are possible.

INSERT TABLE 2 ABOUT HERE

Employing time series data on 20 or so measures relating to rainfall, evapotranspiration, groundwater depth, useable recharge, ground and surface water relativities, agricultural and cropping intensities, cropping pattern, rice intensity in irrigation, spread of technology involving areas allocated to HYVs of rice, incidence of different sources of irrigation, a set of composite variables are derived.

On the basis of prior characterization, one could consider extracting three, four or five composite factors. After a fair bit of trial and error, three and four factors each were identified for kharif, rabi and annual crops respectively. The number of factors was determined by a combination of (a) restricting the eigenvalues to unity or above; and (b) whether the extracted factors made any sense or were amenable to meaningful interpretation. Tables A2, A3 and A4 respectively refer to the component matrix for kharif, rabi and annual crops. The information presented in Tables A2, A3 and A4 warrant some discussion.

Information presented in Table A2 suggests that three factors can be classed as (a) HYDROCLIM (combination of climatic and hydrological variables including annual and seasonal rainfall, annual and seasonal evapotranspiration and their variabilities, and useable recharge); (b) AGINTENS (combination of net a gross agricultural intensities, cropping intensity and crop concentration ratio); and (c) TECHDIFF (combination of spread of new technology in variables including percentage area irrigated, percentage of total kharif rice area under HYVs). Between them the three factors explain more than 70 per cent of the total variance.

In a similar way, four factors have been identified for each of rabi and annual crops (Tables A3 and A4). Between them, these four factors explain about 76 per cent of the total variance in both cases. While some original variables belong exclusively to a particular category, there are some cross loadings as well. For example, for rabi crop, ANRAIN (annual rainfall) belongs to CLIMATIC and HYDROCLIM factors. Similarly, percentage of rabi HYV area (PCRABIHYV) belong the agricultural intensification factor (AGINTENS) and technological diffusion factor (TECHDIFF). Annual rainfall (ANRAIN) and standard deviation of dry season evapotranspiration (SDETDRY) belong to two factors in case of the annual crop (Table A4). On the whole however, there are very few cross-loadings implying reasonable distinctiveness in the characterization of factors.

5 EXPLAINING DISTRICT-LEVEL WATER PRODUCTIVITY DIFFERENCES

This section provides an explanation of the differences that exist in levels of water productivity across districts and over time. A discussion of results follows. In doing so it uses the factors that were extracted in the preceding section as explanatory variables. The list of explanatory factors is expanded by including the following variables:

Time: Measures time trend; 1968 = 1 and so on.

BASIN: Location of the district; = 1, if the district is located in the Ganges-dependent area, 0 otherwise.

POLICIREG1: Policy regime 1; =1 if the data relate to the 1981-90 (inclusive) period, 0 otherwise. This represents the period of policy transition from a regulated policy regime to one based on greater reliance of the market forces.

POLICIREG2: Policy regime 2; = 1 if the data relate to the 1991-2004 (inclusive) period, 0 otherwise. This is the phase in which the economy experienced the deepest penetration of market forces.

5.1 Results

Given that this study uses panel data, ordinary least squares estimates are likely to be inappropriate due to the presence of heteroscedasticty and first-order autocorrelation. This was confirmed by likelihood test ratio for heteroscedastity and Wooldridge test (Wooldridge 2002) for autocorrelation. Table 3 provides the relevant test statistics which suggest the presence of these two problems. In view of these problems, the present study employs generalized least squares (GLS) estimates corrected for heteroscedasticty and first-order autocorrelation. GLS estimates are presented separately for kharif, rabi and annual rice crops in Table 4.

INSERT TABLE 3 ABOUT HERE

Water productivity levels for all rice crops have experienced statistically significant time trends. For the rabi crop the trend is numerically much smaller (only two grams per year) compared to the kharif and annual crops (respectively seven and six grams per year). This is probably due to higher base values for the rabi crop.

The location of the district represented by the dummy variable BASIN, displays statistically significant and substantially negative effects on the level of water productivity for all rice crops. A district located in the Ganges-dependent area is likely to have a lower water productivity level (by 18 grams) relative to that in a district outside of it. The corresponding figures for the rabi and annual rice crops are 37 and 26 grams respectively.

The climatic (CLIMATIC) and hydro-climatic (HYDROCLIM) factors display mixed effects on levels of water productivity. The coefficient of the HYDROCLIM variable is not statistically significant for the kharif crop while it is significantly negative and positive respectively for the rabi and annual rice crops. The coefficient of CLIMATIC is significantly negative in both cases but the effect is nearly three times as strong for the rabi crop relative to that for the annual crop.

The agricultural intensification factor (AGINTENS) is only significant at the 10 per cent level for the kharif crop but not significant at all for the annual crop. This contrasts with its effect on the rabi crop which is significantly and substantially positive. Technological diffusion variable (TECHDIFF) has significantly positive and substantive effect on water productivity level for all crops.

Policy transition to market economy (POLICIREG1) has had a strong negative effect on the level of water productivity for the rabi crop relative to the policy regime which was characterized by significant state control and subsidy. Its coefficient is significant at the 5 per cent level. For the kharif crop it is significant at the 10 per cent level and has had a positive effect. On the other hand, it is not significant at all for the annual crop.

The phase in which the economy of Bangladesh experienced the deepest penetration of market forces (POLICIREG2) did not have any significant effect on levels of water productivity for kharif and annual crops of rice. This contrasts with the significant and substantial negative effect of this factor on the rabi crop water productivity.

INSERT TABLE 4 ABOUT HERE

The results presented above suggest that:

- Location of a district in the Ganges-dependent area is likely to have a consistently negative effect on water productivity for all rice crops with the rabi crop being more substantially affected.
- Technological diffusion has had a consistent and substantial positive effect on the water productivity levels for all rice crops.
- Effects of all other factors have neither been consistently significant from a statistical point of view nor from a numerical point of view for all rice crops. Furthermore, they have not been consistently positive or negative.

5.2 Discussion of Results

This section is devoted to a discussion of salient features the empirical results with an analysis of the role of variables underlying some factors such as (i) technical diffusion; (ii) agricultural intensification; (iii) Ganges-dependent vs. non-Ganges-dependent area; and (iv) policy regime.

***Technological diffusion* (TECGDIFF)**

The underlying variables that constitute this factor include amongst others:

1. Groundwater irrigation as a percentage of gross irrigated area. One might call this the incidence of groundwater area (GWIPCTOT);
2. Ratio of groundwater irrigated area to surface-water irrigated area (GWSWR);
3. Percentage of of HYV area in khairf, rabi or annual crops of rice (PCKHHYV, PCRABIHYV or PCHYVALL); and
4. Mean groundwater depth (MEANGWD)

Underlying variables 1, 2 and 4 imply high dependence on groundwater. Thus the productivity of water critically depends on: (a) expansion of area under HYV rice; and (b) significant use of environmental resources primarily groundwater. Increasing dependence on groundwater extraction has led to significant lowering of groundwater tables. The maximum groundwater depth is significantly positively correlated with the incidence of groundwater irrigation as measured by the percentage of groundwater-irrigated area in gross area irrigated. The maximum groundwater depth has increased significantly between the early 1970s and the early 2000s.

Table 5 presents changes in the five yearly average maximum groundwater depths between early 1970s and early 2000s in selected regions of Bangladesh for illustrative purposes. Dhaka, which includes mostly the city area, has suffered the greatest increase in the maximum groundwater depth (by 42 meters). This seems consistent with the finding that groundwater table in Bangladesh's capital city, Dhaka has declined by an average of 1 m/year over the last three decades (Zahid and Ahmed 2006, p.40). However, this phenomenon may not be agriculture related groundwater usage but due to a five and a half-fold increase in Dhaka city's population from 1.5 million in 1971 to 9.7 million in 2001.

What is worrying is the case of Gazipur (a constituent district of greater Dhaka) which has experienced an increase of 22 meters in its groundwater depth between the two end points in time. Two constituent districts (Naogaon and Natore) of greater Rajshahi district have experienced similar increases (10 meters) in maximum groundwater depth. However, the case of Noagaon is quite different from that of Natore in that the former's maximum groundwater depth was four times as high (20 meters) as that of the latter (5 meters) in the initial period. Apparently, high rainfall areas of Bangladesh such as Comilla, Kishoreganj and Mymensingh have experienced groundwater depth increase of more than nine meters.

Given that there is a significant positive correlation between incidence of groundwater usage in agriculture and groundwater depth, it is plausible that groundwater is only renewable partially. Evapotranspiration is consistently higher than dry season rainfall with increasing dependency on groundwater irrigation throughout Bangladesh.

***Agricultural intensification* (AGRINTENS)**

Four major variables underlie this factor:

1. Net agricultural intensity (NAI) representing net cultivated area as a percentage of total land area;
2. Gross agricultural intensity (GAI) measured by gross area cultivated as a percentage of total land area;
3. Cropping intensity (CROPINTN) representing gross cropped area as a percentage net cropped area; and
4. Crop concentration ratio (CROPCONC) representing rice area as a percentage of gross cropped area and measures the incidence of rice cultivation in cropping pattern,

Not surprisingly, net agricultural intensity is on the decline. This is because with increase in population and the competing demand for land for urbanization, human settlement and roads and highways, amongst other things, land area available for crop production is declining. Data from various issues of the *Yearbook of Agricultural Statistics of Bangladesh* suggest that Over the 30 year period to the early 2000s, the net-cropped area declined by 6.8 per cent (578 thousand hectares) while gross cropped area increased by 11.3 per cent (1.585 million hectares) over the same period. This has resulted in a significant increase in the cropping intensity (from 146.5 to 177.1 per cent). Crop concentration ratio presented in Table A1 shows that in many districts (Chittagong, Khulna, Kishoreganj, Mymensingh, Noakhali and Sylhet), more than or close to 90 per cent of gross cropped area is planted with rice, which represents a virtual monoculture. In all the districts, the crop concentration ratio is on the increase over time leading to greater incidence of rice cultivation over time. However, as can be seen from Table A1, the water scarce districts of Rajshahi, Jessore and Kushtia like other districts in Bangladesh are characterized by high crop concentration ratios, they are lower than elsewhere in the country. For instance, the crop concentration ratio for Kushtia was only about 68 per cent in 2004 (63 per cent in 1970). Percentage of gross cropped area allocated to rice in Jessore has remained stable at about 76 per cent. For Rajshahi, about 83 per cent of gross cropped area was allocated to rice in 2004 compared to 81 per cent in 1970. One implication for the increasing incidence of rice is that the process of agricultural production has become more water dependent. In the dry season – rice and pulses are competing crops. The former is at least one and half times more water-intensive than pulses. Furthermore, pulses are of considerably shorter duration than rice (BARC 2001, p.116). Why then farmers allocate more land to rabi rice than pulses? There are two likely reasons for this. First, technological progress in pulses has lagged far behind that in rice. Second and more importantly, rice is the staple food. While changing food habits is a long-term phenomenon, partial reallocation of land away from rice in the dry season will have significant water-saving implications.

***The Ganges vs. non-Ganges-dependent areas* (BASIN)**

One disconcerting feature is the lower level of rice water productivity in the Ganges-dependent area districts (Barisal, Faridpur, Jessore, Khulna, Kushtia, Pabna, Patuakhali and Rajshahi) relative to the non-Ganges-dependent area. This is not consistent with water endowment pattern, given that much of the Ganges-dependent area suffers from relative water scarcity. Taking the severe and the very severe drought categories, together well over two million hectares (nearly 30 per cent of the net cultivable area) are drought affected (BBS 1999, p.69). The areas are located in the GDA districts of Jessore, Kushtia and Rajshahi, and Chapai Nawabganj. Parts of Dhaka, Tangail, Bogra and Dinajpur districts are susceptible to droughts of sever intensity. About more than 580 thousand hectares of agricultural land constituting a quarter of net cultivable area in Rajshahi and Chapai Nawabganj are very severely drought affected. No other areas of Bangladesh are exposed to the risk of intensity and extent of droughts as these two districts.

Greater risk of drought combined with increasing extraction of groundwater resources can exacerbate the impact of drought on crop yield per hectare. Information limitations preclude the possible of an in-depth analysis of the effect of drought on crop productivity per hectare. Karim and Iqbal (1997) provide an estimate of loss of crop yield of transplanted aman (kharif) rice due to drought all three stages of the crop production process (pinnacle initiation, heading to milk and milk to maturity). Karim and Iqbal (1997, p.75) further report that its impact is particularly sever during the milk-to-maturity stage. There are also significant spatial variations of the effect of drought. Given higher incidence of droughts in the northern districts of Bogra and Rajshahi and western district of Jessore, these are more adversely affected than the central district of Dhaka and the eastern districts of Comilla and Sylhet. Furthermore, the duration of the drought is much longer (13 days each) for Jessore and

Rajshahi compared to eight and four days respectively for Comilla and Sylhet. Drought stress affected yield is only 43 and 38 per cent respectively of the no-drought-stress yield. The Ganges-dependent area is characterized by high climatic variability and 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).

***Policy regime* (POLICIREG1 and POLICIREG2)**

Since the 1980s, Bangladesh has been pursuing a policy of, initially transition to and subsequently a complete deregulation of the agricultural input market. These were done primarily on the basis of World Bank and IMF prescriptions under the structural adjustment program. This change in policy led to free market sales of critical agricultural inputs such as chemical fertilizers and irrigation machinery (shallow and deep tube wells, and low lift pumps). This policy change led to an increase in the price of all agricultural inputs reflecting their 'true' price. Furthermore, the policy makers also had to consider the highly porous border with India and a significantly lower fertilizer price in Bangladesh than in India would always encourage illicit border trade. Thus bringing the agricultural input prices to their scarcity value in itself might not have resulted in the adverse effect on rabi rice water productivity. However, the problem lay elsewhere.

While few would disagree with such a policy rationalization, what was really lacking was a proper institutional arrangement underlying the supply and distribution of different inputs that were essential for irrigation. Uncertainty and disruption in the diesel and power supply for irrigation are quite common. Rabi HYVs of rice are completely dependent on irrigation and timely application of complementary inputs such as chemical fertilizers. Given that the dry season evapotransipration exceeds precipitation in most districts but especially in the drier districts, inadequacy and untimely availability of critically important inputs is, therefore, likely have a significant adverse effect on the rabi crop than the kharif crop for which irrigation is only supplementary. This could be the underlying reason for the significant negative signs of the two policy regime dummy variables for the rabi season.

6 IMPLICATIONS

6.1 Water Resource Use Implications

In light of the preceding discussion, it seems clear that increasing reliance on groundwater resources underpins in the expansion of area under HYVs of rice during the rabi season and consequently water productivity. As of 2004, rabi rice for Bangladesh as whole, accounted for 55 per cent of total rice output with 39 per cent of the gross area. This contrasts with the corresponding 1970 figures of 20 and 10 per cent respectively. These figures mask considerable interdistrict variations. For example, the share of rabi rice output in total rice in Tangail, Pabna, Dhaka, Kishoreganj, Comilla, Faridpur and Bogra are well over two thirds. Three of these districts (Tangail, Dhaka and Bogra), are located in the drought-prone areas. For the Ganges-dependent and drought-prone districts of Rajshahi, Jessore and Kushtia the share of rabi rice output is at least 50 per cent of the total. The rabi crop of rice in recent years depends almost exclusively on groundwater irrigation. This represents a complete reversal of the scenario of the early 1970s when irrigation was mostly dependent on surface water. This, combined with the rapid expansion of rabi HYVs, has made the production process cropping of rice highly groundwater intensive.

Water productivity for the rabi rice is appreciably higher than that for kharif crop. The former is underpinned by groundwater irrigation while the latter is primarily rainfed but supplemented by irrigation (more from groundwater than surface water usage). More importantly, while HYVs of kharif rice for Bangladesh as a whole have spread to just over 50 per cent to rice area during the season, nearly 100 per cent of the rabi rice crop is under by HYVs. The percentage area under kharif HYVs vary significantly across districts. As can be seen from Table A1 in 2004, Bogra (72.4%), Chittagong (82.2%), Jessore (77.6%), Kushtia (86.1%), Rajshahi (78.6%), Rangpur (74.2), Dinajpur (66.4) and Kishoreganj (60.6%) are standout performers in adoption of kharif HYVs. The kharif HYV rice adoption rates in the Ganges-dependent districts of Kushtia, Rajshahi and Jessore are particularly noteworthy.

On the whole, Bangladesh has become more rice-intensive as measured by the percentage of gross cropped area allocated to rice which has increased significantly over time for all the districts. This implies that other crops may be facing a ‘crowding out’ syndrome. The situation, while showing a similar trend, as of 2004, rice intensity is appreciably lower in the Ganges-dependent districts of Kushtia (67.8), Faridpur (63.2) and Jessore (75.9) than most other districts and well below the overall Bangladesh average (over 80 per cent).

The implication of increasing rice intensity in Bangladeshi cropping pattern is the resulting increase in usage of water in general and groundwater in particular. Thus the rice economy of Bangladesh has become more environment-intensive and less environment-augmenting (saving) in orientation. This is manifested in increasing intensity of land use (increasing cropping intensity and gross agricultural intensity) and a phenomenal increase in the ground-surface water usage ratio. The latter typifies a process of external rather than internal water-augmentation. The former manifests itself in horizontal expansion of area under irrigation especially during the dry season while the latter refers to bringing about qualitative change by increasing productivity of water through its efficient usage. In the former case irrigation may expand to marginal areas e.g. areas with relative scarcity.

6.2 Sustainability Implications

At this stage it is useful to ask two related questions:

1. How sustainable is the pattern of water resource use in Bangladeshi crop production?
2. Where does the process of crop production in Bangladesh lie in the spectrum of views on sustainability?

Answers to the above require a brief discussion of the spectrum of views on the conditions of sustainability. Following Pearce (1993) and Turner et al (1994) one could identify a range of views on sustainability ranging from a position of very weak sustainability through to very strong sustainability (Klassen and Opschoor 1990; Daly and Cobb 1989). Figure 3 encapsulates these views which warrant a brief discussion.

Very weak sustainability (Solow-Sustainability) merely requires that the overall stock of capital assets should remain constant over time. It embodies two important features: (a) assumes man-made-capital as a suitable bequest for posterity; and b) presupposes a high degree of substitution between natural resources and man-made capital. Weak sustainability (modified Solow-sustainability) implies a sustainability constraint that restricts somewhat 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 declining level of environmental quality and natural resource availability.

Strong sustainability (ecological economics approach; Turner et al 1994, p.271)) rests on: (a) uncertainty about ecosystem functioning and its total service value; (b) irreversibility in the context of degradation (or loss) of environmental resource; (c) aversion to loss by many individuals with the process of environmental degradation; and (d) the criticality or non-substitutability of some components of natural capital with other types of capital. On the whole, two salient features characterize strong condition of sustainability. Firstly, it emphasizes on trying to hold the stock of natural resources constant. Secondly, it assumes only a limited degree of substitutability with a view to taking care of the posterity. Very strong sustainability (Stationary state sustainability) reduces the 'call for a steady-state economy based on the thermodynamic limits and the constraints they impose on the overall scale of the macroeconomy. ... Zero economic growth and zero population growth are required for a zero increase in the scale of the macroeconomy'.

The preceding discussion on the conditions of and spectrum of views on sustainability, and the resource use pattern in Bangladeshi crop sector seems to suggest that the discourse of agricultural development is preeminently environment-using, not environment-saving. The two fundamental environmental resources of Bangladesh, more specifically land and water, are under considerable strain from intensification and extension of agriculture facilitated by the green revolution technologies, deforestation and loss of natural vegetation cover. Consequences of resource depletion and environmental pollution have not been given enough attention in many developing countries including Bangladesh. Unsustainable extraction of groundwater, indiscriminate use of pesticides and unbalanced use of chemical fertilizers led to degradation of the environment and the ecosystem.

Furthermore, a characteristic feature of groundwater irrigation is the increasing AND overwhelming dominance of the use of shallow tube wells. Available information from the Department of Extension suggests that in the 2009 boro season more than 76 per cent of the total irrigated area is attributable to shallow tubewell irrigation while only about 2 per cent is irrigated by deep tube wells. In general, shallow tube well irrigation (groundwater) requires 17 per cent more diesel per acre than low lift pumps (surface water) and 8 per cent more than for an acre irrigated by deep tube well. Increasing dependence on groundwater especially by shallow tube wells implies increasing fossil fuel usage. This has adverse environmental implications.

There has been a significant decline in soil quality across all the twenty nine agro-ecological zones (AEZs) of Bangladesh (Hasanuzzaman 1998, pp.97-98; Bramer 1997, p.7). Hasanuzzaman, however, (1998) and Bramer (1997) provide only a partial picture of the soil nutrient deficiency. For instance, boron and magnesium levels are not known for all AEZs. This notwithstanding, the problem of land quality degradation especially due to sulphur and zinc deficiency seems serious. Organic matter in soils declined quite significantly between 1969 and 1989 in AEZs with high and medium high and elevation (BBS 1999, p.166). The old Meghna estuarine floodplain has suffered a massive decline of nearly 46 per cent followed by northern and eastern hills (25 per cent). According to Ali et al (1997, p.889) the depletion in soil quality (fertility) in Bangladesh has resulted from intensive exploitation of land without adequate replenishment.

In light of the above, it is clear that Bangladesh agriculture only meets the conditions of weaker sustainability (growth optimism) rather than stronger sustainability (greener) end of the spectrum. Growing focus on rice boro rice may meet the present needs but may be unsustainable given the degradation of the quality of two critical inputs in agriculture – land and water especially groundwater. The process has exposed the fragility of the physical environment. It is unclear without further research whether resource degradation or damage to the physical environment represents a transitory phase or may be irreversible.

7 POLICY OPTIONS

In light of the discussion in Sections 5 and 6, this section explores some policy options for Bangladesh. Given the resource use pattern in general and water use pattern in particular which is the focus of this paper, the centerpiece of the policy options is achieving internal water augmentation. This implies ensuring the best use of the resource which is short supply (in this case, water). This seems paradoxical given that Bangladesh is located in the high rainfall zone of the world. This however, masks high seasonality in precipitation with more than 90 per cent of it taking place in the four monsoonal months between June and October. Thus Bangladesh suffers from excess as well as shortage of water. Furthermore, there is considerable uncertainty in the arrival of monsoonal rain. As a result crop production faces the risk of regular bouts of droughts and floods of differing severity with significant adverse implications for crop production.

Internal water augmentation can be achieved in several ways embodying two broad ways. These 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 relative dependence on the rabi and an expansion of the scope of the kharif rice crop. These two points warrant some discussion.

Despite significant expansion in rice area under HYV in the dry (rabi) season, actual yields on average are 2 tonnes per hectare below the potential. Point (a) above represents only 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 even increased by bridging the gap between potential and actual yields through better input and resource management. The land released from dry season rice cropping could be allocated to other crops of higher nutritional value but of less water consuming in nature. According to Afzal et al (2004, p.60) all major varieties provide about the same amount of energy as rice but nearly four times as much protein, 8-18 times as much calcium but no more than 80 per cent of carbohydrate. Point (b) implies the need for significant expansion of HYV rice technology in the kharif season through: (i) stronger provision for supplementary irrigation to kharif HYV areas; and (ii) greater adaptability of HYVs to various environmental conditions.

The above strategy is underpinned, amongst others, by three categories of policy options: market-based, R & D-based and institutional support. The remainder of this section provides a brief discussion of these options. Figure 4 encapsulates the principal elements of the policy options.

Market-based option

This option relies on setting input prices to close to their scarcity so they reflect resource endowment. In Bangladesh, pricing of material inputs such as fertilizers, pesticides and irrigation equipment and other machinery has rationalized through policies that have evolved in the 1980s and 1990s. This included the removal of subsidies and exchange rate distortions, However, environmental goods such as groundwater, has been as a ‘free’ good even though it is a scarce resource in many parts of Bangladesh and is becoming more so with time. 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 engine capacity a fee can be imposed just to demonstrate at least partially the true value of this environmental good. The former is difficult to enforce in practice but the latter is relatively easier to implement. One other instrument complementary to those mentioned above is to design incentive mechanisms for innovation of the environment-saving type. e.g. water and energy saving mechanical innovations.

R & D-based option

The essential elements of this option include *inter alia*

- Developing crop varieties that are less water-using (water-saving). These include rice as well as non-rice crops. 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/providing incentives for greater usage of surface water for irrigation given its relative abundance in some parts of Bangladesh. This assumes greater significance because rapid urbanization will put considerable strain on groundwater tables for supply of water for domestic usage in urban areas.

- Of paramount importance is to extend and intensify research efforts toward developing HYVs of non-rice crops e.g. pulses and vegetables which are financially attractive to farmers and can partially but effectively replace rabi rice crop cropping. These crop varieties must contain multiple attributes involving wider adaptability to temperature variations, higher yields and lower consumptive water usage. This entails process innovations.
- R & D efforts also need to concentrate on product innovation such as energy-saving mechanical innovation.

Institutional support

Internal water augmentation in agricultural crop production requires strong institutional arrangements. The central elements of this option warrant discussion. There are several ways in which uncertainty surrounding cropping pattern change from rice to non-rice crops in the rabi season and expanding the coverage of the HYVs of rice in the kharif season can be managed or minimized.

- First, input supply and delivery system involving adequate and timely availability of critical inputs such as fertilizers and irrigation water needs to be stronger than at present. Uncertainty in energy supply (power and diesel) has a detrimental effect on crop yields. This also affects water productivity.

- There must be the provision for crop insurance to reduce the risk of crop failure due to natural phenomena such as droughts and floods of differing severity. This is of considerable importance given serious consequences of crop failure especially for the smaller and marginal farmers.
- There needs to be significant strengthening of the linkages involving education extension and research. This is absolutely vital for awareness building and sensitization on resource use and resource conservation.
- The overwhelming dietary dependency on rice needs a rethink. However, this is a long-term phenomenon given that food habits are an integral part of the socio-cultural milieu. Reduction in dietary dependency on rice and more toward pulses, for example, could be significantly water-saving but at the same time more nutritious. This could be achieved through a proper awareness building about the dietary changes.

The above do by no means represents an exhaustive list of options. However, it embodies some of the major options that Bangladesh needs to purse in order to achieve internal water augmentation.

8 CONCLUSION

This paper has identified factors that explain the differences in the levels of rice water productivity among Bangladeshi districts over period of nearly four decades. Factors embodying variables that represent variations in climatic and hydro-climatic conditions, technological diffusion, and agricultural intensification did appear to explain interdistrict variations in levels of water productivity. However, all of them were not consistently significant for the two main rice crops (rabi and kharif). Other variables that significantly influenced the variations in water productivity were district location (Ganges versus non-

Ganges-dependent area districts) and policy regime dummy variables typifying (a) the decade of transition to market economy; and (b) the period of exclusive reliance on market forces without proper institutional support for input supply and delivery, did have significant negative effect on levels water productivity in the dry season. One encouraging sign is the statistically significant positive time trend in levels of water productivity. This implies a corresponding decline in the consumptive water use per kilogram of rice produced.

This paper argues that the process of crop production and attendant consumptive water use especially groundwater only meets the conditions of weak sustainability criteria. Furthermore, foodgrain production based on trends in growth groundwater usage seems unsustainable. The process of internal land augmentation has been underpinned by a process of external water augmentation. The central idea that this paper advocates is that Bangladesh needs to achieve, internal water augmentation to enhance and sustain land and water productivity. It advocates a set of policy options which in complementarity with one another are likely to achieve this goal. These are both market-based and non-market based in orientation. Institutional support is of critical importance.

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Table 1 Descriptive Statistics of Water Productivity Measures, Bangladesh Districts, 1968-2004

District	Average rice water productivity (kilogram per m^3 of CWU)			Coefficient of variation (%)		
	Kharif	Rabi	Annual	Kharif	Rabi	Annual
Barisal*	0.287	0.471	0.306	19.3	13.6	18.4
Faridpur*	0.216	0.516	0.280	24.2	17.2	34.6
Jessore*	0.347	0.459	0.358	36.9	14.1	35.0
Khulna*	0.343	0.355	0.344	28.1	20.1	25.9
Kushtia*	0.314	0.424	0.325	33.7	22.3	36.1
Pabna*	0.275	0.493	0.335	33.7	17.8	35.5
Patuaklhali*	0.290	0.382	0.297	23.0	27.5	19.7
Rajshahi*	0.336	0.437	0.358	31.3	24.9	31.4
Bogra	0.387	0.481	0.412	25.1	24.5	26.8
Chittagong HT	0.423	0.421	0.422	23.5	11.3	19.7
Chittagong	0.470	0.451	0.459	22.9	11.1	16.0
Comilla	0.358	0.522	0.407	22.5	22.5	22.5
Dhaka	0.293	0.472	0.367	23.9	17.2	25.1
Dinajpur	0.347	0.509	0.367	18.3	12.8	22.0
Jamalpur	0.320	0.480	0.371	20.8	16.3	21.1
Kishoreganj	0.348	0.447	0.400	25.1	20.0	22.4
Mymensingh	0.331	0.438	0.362	21.6	24.4	24.2
Noakhali	0.328	0.481	0.357	22.8	16.0	21.7
Rangpur	0.362	0.472	0.381	24.6	17.8	26.1
Sylhet	0.339	0.344	0.342	20.5	21.3	19.7
Tangail	0.293	0.570	0.378	24.7	14.1	27.3

*Ganges-dependent area

Source: Based on data from Yearbook of Agricultural Statistics of Bangladesh (various issues); Water Resource Planning Organization (WARPO) and Centre for Environmental and Geographical Information System (CEGIS).

Table 2 Variables underlying probable determinants of water productivity measures

Variables	**Description**	**Variable Characterization**
SDMEFFR	Standard deviation of monthly effective rainfall	Climatic
SDMMDEFFR	Standard deviation of daily effective rainfall	Climatic
SDMRF	Standard deviation of monthly rainfall	Climatic
SDMMDRF	Standard deviation of daily rainfall	Climatic
ARAIN	Annual rainfall	Climatic
SWPCTOT	Surface water irrigation as % of gross irrigated area	Technology diffusion
GWIPCTOT	Ground water irrigation as % of gross irrigated area	Technology diffusion
GWSWR	Ratio of ground water irrigated area to surface water irrigated area	Technology diffusion
MEANGWD	Mean ground water depth	Hydrological
USRECHARGE	Usable recharge (75% of potential recharge)	Hydrological
SDMMDETP	Standard deviation of daily evapotranspiration	Hydrological
RABIPCIR	Rabi rice area as percentage irrigated of gross irrigated area	Technology diffusion
PCRWIR	Rabi rice and wheat area irrigated as percentage of gross irrigated area	Technology diffusion
RICEPCIR	Rice area irrigated as percentage of gross irrigated area	Technology diffusion
CROPCONC	Cropping pattern concentration ratio (% of gross rice area in gross cropped area used as proxy)	Agricultural intensification
PCHYVALL	% of HYV area in all rice	Technology diffusion
PCKHHYV	% of HYV area in kharif rice	Technology diffusion
PCRABIHYV	% of HYV area in rabi rice	Technology diffusion
CROPINTN	Cropping intensity (gross cultivated area as % of net cropped area)	Agricultural intensification
GAI	Gross agriculture intensity (gross cultivated area as % of total land area)	Agricultural intensification
NAI	Net agriculture intensity (net cultivated area as % of total land area)	Agricultural intensification

Table 3 Tests for heteroscedasticity (likelihood ratio test) and first-order autocorrelation (Wooldridge test)

Test for	Kharif rice crop		Rabi rice crop		Annual rice crop	
	Test-statistic	p-value	Test-statistic	p-value	Test-statistic	p-value
Heterokedasticity	141.19	0.000	110.01	0.000	98.62	0.000
First-order autocorrelation	49.59	0.000	12.18	0.002	25.69	0.000

Table 4 Results of generalized least squares estimates after accounting for heteroscedasticty and first-order autocorrelation

Explanatory Variable	Kharif rice crop		Rabi rice crop		Annual rice crop	
	Coefficient (2)	p-value (3)	Coefficient (4)	p-value (5)	Coefficient (6)	p-value (7)
TIME	0.006	0.000	0.002	0.008	0.006	0.000
BASIN	-0.018	0.007	-0.037	0.000	-0.026	0.000
CLIMATIC			-0.008	0.000	-0.003	0.036
HYDROCLIM	-0.001	0.677	-0.007	0.005	0.003	0.048
AGRINTENS	0.004	0.082	0.012	0.000	0.003	0.168
TECHDIFF	0.022	0.000	0.025	0.000	0.031	0.000
POLICIREG1	0.028	0.053	-0.037	0.022	0.016	0.175
POLICIREG2	-0.003	0.775	-0.021	0.052	-0.007	0.376
Intercept	0.215	0.000	0.448	0.000	0.248	0.000
N	764		764		764	
Wald test	626.35		229.66		1180.13	

Table 5 Changes in the maximum groundwater depth between early 1970s and early 2000s in selected regions of Bangladesh

Region		Approximate maximum groundwater depth (meter)		Range between maxima (meter)
Greater district	Constituent district	Early 1970s	Early 2000s	
DHAKA	Dhaka	8	50	42
DHAKA	Gazipur	8	30	22
RAJSHAHI	Naogaon	20	30	10
RAJSHAHI	Natore	5	15	10
RAJSHAHI	Rajshahi	16	19	3
BOGRA	Bogra	5.5	10	4.5
BOGRA	Joypurhat	3.5	10	6.5
JESSORE	Jessore	1.5	8	6.5
KISHOREGANJ	Kishoreganj	6.5	15	8.5
KUSHTIA	Kushtia	5.5	10	4.5
MYMENSINGH	Mymensingh	6.5	16	9.5
COMILLA	Comilla	5.5	15	9.5
DINAJPUR	Dinajpur	5	10	5

Source: Based on data from CEGIS.

Table A1 Dynamics of Changes in Rice Water Productivity, Indicators of Technology Diffusion and Agricultural Intensification, Bangladesh Districts, 1970 (for Jamalpur 1980), 1990 and 2004

District	Year	Kilograms of rice per m^3 of water			Cropping intensity (%)	Net agricultural intensity (%)	Gross agricultural intensity (%)	Rice in gross irrigated area (%)	Ground water in gross irrigated area (%)	Groundwater-surface water ratio	Crop concentration ratio	HYV as a percentage total rice area		
		Kharif	Rabi	All								Rabi	Kharif	All
Barisal	1970	0.176	0.568	0.218	148.8	69.8	103.9	99.7	0.000	0.00	84.6	89.3	0.7	7.7
Barisal	1990	0.308	0.424	0.323	149.1	65.9	98.2	84.9	0.000	0.00	74.5	93.2	5.7	14.6
Barisal	2004	0.368	0.576	0.409	166.3	52.0	86.5	86.3	0.372	0.00	82.9	95.9	13.5	26.3
Bogra	1970	0.289	0.405	0.295	155.0	76.1	118.0	57.0	9.395	0.10	81.9	44.2	2.2	3.9
Bogra	1990	0.453	0.461	0.457	202.0	69.1	139.5	83.3	90.974	10.08	86.0	99.9	52.3	72.2
Bogra	2004	0.493	0.598	0.557	214.7	76.4	164.0	80.1	98.197	54.47	83.1	99.8	72.4	87.1
Chittagong	1970	0.302	0.527	0.356	135.2	43.4	58.6	86.7	1.914	0.02	90.6	71.5	4.3	16.8
Chittagong	1990	0.472	0.287	0.409	181.3	32.5	59.0	85.1	8.470	0.09	91.9	99.9	80.9	85.5
Chittagong	2004	0.602	0.499	0.568	177.7	33.1	58.9	78.3	12.935	0.15	89.0	100.0	82.2	86.9
Chittagong HT	1970	0.271	0.389	0.293	160.1	5.3	8.5	93.8	0.107	0.00	84.7	33.2	2.3	6.7
Chittagong HT	1990	0.485	0.403	0.468	146.9	5.9	8.7	86.8	0.000	0.00	62.3	98.2	65.6	70.5
Chittagong HT	2004	0.578	0.492	0.556	152.5	7.4	11.2	65.4	0.000	0.00	58.0	100.0	78.3	82.6
Comilla	1970	0.282	0.463	0.308	161.0	80.9	130.3	98.7	2.443	0.03	82.1	55.8	1.4	7.3
Comilla	1990	0.385	0.525	0.433	197.8	68.0	134.5	79.9	40.132	0.67	82.3	98.9	38.1	55.8
Comilla	2004	0.425	0.656	0.567	176.5	66.8	117.9	87.1	51.769	1.07	85.0	98.7	62.4	82.5
Dhaka	1970	0.229	0.402	0.262	145.2	67.6	98.2	82.5	1.197	0.01	61.0	39.3	1.3	6.8
Dhaka	1990	0.276	0.501	0.385	183.3	59.1	108.3	87.4	58.727	1.42	71.9	96.3	21.7	51.3
Dhaka	2004	0.373	0.664	0.556	172.8	53.0	91.7	89.5	69.041	2.23	77.5	97.7	37.6	70.6
Dinajpur	1970	0.291	0.330	0.292	141.4	74.9	105.8	80.1	54.332	1.19	81.3	85.0	2.8	3.6
Dinajpur	1990	0.422	0.533	0.437	172.3	69.9	120.4	58.5	80.429	4.11	85.5	98.2	35.2	41.9
Dinajpur	2004	0.437	0.655	0.526	187.7	69.6	130.7	63.1	95.962	23.76	85.4	100.0	66.4	78.3
Faridpur	1970	0.177	0.486	0.193	163.2	68.6	112.1	98.1	0.199	0.00	66.6	60.5	0.0	2.3
Faridpur	1990	0.236	0.529	0.344	178.4	73.8	131.6	89.0	57.568	1.36	55.6	74.7	4.8	25.5
Faridpur	2004	0.239	0.529	0.344	183.1	63.6	116.4	79.9	53.476	1.15	63.2	96.6	13.9	46.2
Jamalpur	1980	0.279	0.363	0.288	172.4	78.8	135.9	86.1	89.0	13.9	90.2	19.7	0.245	80.3
Jamalpur	1990	0.248	0.486	0.314	196.3	64.1	125.9	88.7	84.034	5.26	85.8	89.7	9.8	27.2
Jamalpur	2004	0.439	0.621	0.541	199.8	67.6	135.0	82.8	90.702	9.76	81.0	98.1	53.2	74.4
Jessore	1970	0.205	0.483	0.214	130.7	75.0	98.0	96.4	10.156	0.11	76.4	73.9	1.3	2.8
Jessore	1990	0.422	0.501	0.448	190.2	69.6	132.4	82.1	75.587	3.10	68.1	99.3	49.6	60.0
Jessore	2004	0.519	0.588	0.563	208.5	68.1	142.1	82.0	91.963	11.44	75.9	99.7	77.6	87.7

Table A1 continued

Khulna	1970	0.187	0.334	0.199	124.3	33.4	41.6	70.8	0.667	0.01	89.0	37.6	0.8	2.6
Khulna	1990	0.383	0.354	0.379	132.4	33.8	44.7	75.9	70.547	2.40	90.2	75.7	19.7	25.0
Khulna	2004	0.230	0.356	0.284	134.7	32.0	43.1	80.0	62.058	1.64	89.3	93.1	54.6	64.1
Kishoreganj	1970	0.390	0.418	0.406	157.0	71.1	111.6	99.5	0.175	0.00	75.7	16.3	0.4	6.1
Kishoreganj	1990	0.475	0.650	0.586	161.8	64.6	104.6	97.3	36.061	0.56	88.5	82.4	35.1	55.6
Kishoreganj	2004	0.214	0.386	0.216	157.4	62.1	97.8	97.3	59.145	1.45	89.6	93.8	60.6	79.4
Kushtia	1970	0.376	0.439	0.384	132.5	73.4	97.3	92.9	0.824	0.01	63.2	63.2	2.9	3.5
Kushtia	1990	0.238	0.424	0.256	191.3	66.4	127.1	59.0	58.308	1.40	67.1	97.3	42.5	47.8
Kushtia	2004	0.295	0.486	0.348	201.2	60.4	121.5	57.0	85.489	5.89	67.8	100.0	86.1	91.2
Mymensingh	1970	0.476	0.627	0.545	168.6	76.5	129.0	97.8	4.126	0.04	80.1	31.7	1.7	3.9
Mymensingh	1990	0.222	0.590	0.244	197.0	64.6	127.3	90.8	76.585	3.27	89.0	94.7	27.7	39.3
Mymensingh	2004	0.276	0.455	0.332	196.8	69.5	136.7	92.3	88.377	7.60	91.0	98.5	56.3	72.4
Noakhali	1970	0.360	0.637	0.440	142.4	76.7	109.3	92.1	0.456	0.00	88.7	78.3	1.2	4.7
Noakhali	1990	0.191	0.455	0.202	171.7	57.8	99.2	92.2	10.974	0.12	84.6	97.3	28.6	46.2
Noakhali	2004	0.320	0.521	0.402	182.0	47.1	85.7	88.5	13.364	0.15	83.7	100.0	34.6	49.6
Pabna	1970	0.408	0.665	0.555	148.2	74.1	109.8	69.0	15.541	0.18	71.7	48.3	0.0	1.5
Pabna	1990	0.128	0.552	0.162	187.1	54.0	101.1	93.2	89.485	8.51	73.5	97.6	19.7	45.2
Pabna	2004	0.252	0.263	0.253	199.5	63.9	127.6	86.7	91.571	10.86	74.1	98.7	44.5	71.1
Patuaklhali	1970	0.371	0.365	0.371	131.8	67.2	88.5	98.0	0.000	0.00	90.6	93.5	0.7	6.4
Patuaklhali	1990	0.287	0.347	0.292	141.8	67.4	95.6	95.4	0.000	0.00	74.8	82.2	5.4	5.9
Patuaklhali	2004	0.368	0.511	0.411	156.1	68.4	106.7	47.4	0.000	0.00	84.1	28.1	22.2	22.2
Rajshahi	1970	0.497	0.602	0.553	131.6	72.3	95.2	82.9	2.661	0.03	81.0	24.0	0.1	1.5
Rajshahi	1990	0.306	0.392	0.308	149.1	69.5	103.6	81.4	67.369	2.06	80.7	98.2	34.6	49.6
Rajshahi	2004	0.389	0.473	0.408	156.3	74.9	117.0	72.2	88.741	7.88	82.7	99.9	78.6	88.1
Rangpur	1970	0.452	0.624	0.530	179.5	69.2	124.3	35.6	3.680	0.04	79.0	55.7	1.1	2.0
Rangpur	1990	0.318	0.365	0.334	198.2	67.1	133.1	60.7	77.562	3.46	83.2	99.7	35.8	46.5
Rangpur	2004	0.302	0.342	0.316	196.2	65.8	129.2	73.4	92.702	12.70	84.6	99.8	74.2	84.4
Sylhet	1970	0.356	0.312	0.340	135.1	61.6	83.2	93.3	0.000	0.00	94.8	9.0	1.3	3.6
Sylhet	1990	0.436	0.517	0.477	146.7	54.4	79.8	90.9	7.063	0.08	96.5	46.5	22.7	30.0
Sylhet	2004	0.182	0.480	0.219	149.0	54.2	80.7	88.5	11.210	0.13	95.1	62.9	45.4	53.2
Tangail	1970	0.330	0.555	0.408	149.8	62.4	93.5	97.4	8.730	0.10	68.9	39.4	0.6	4.6
Tangail	1990	0.387	0.736	0.580	170.6	78.7	134.2	94.3	94.731	17.98	69.2	98.8	18.2	42.5
Tangail	2004	0.187	0.334	0.199	186.3	66.7	124.3	91.8	97.170	34.33	78.9	99.4	43.4	72.2

Source: Based on data from sources mentioned in Table 1.

Table A2: Rotated Component Matrix: Factor Extraction (Kharif Rice Crop)

	Factors		
	HYDROCLIM	**AGINTENS**	**TECHDIFF**
Eigenvalue after rotation	5.9	3.0	2.4
% Contribution to total variance after rotation*	36.6	18.6	15.1
WETRAIN	0.946		
ARAN	0.939		
SDANRAIN	0.937		
ETRAINWET	-0.915		
USRECHARGE	0.764		
SDWETRAIN	0.756		
SDETWET	-0.624		
ETWET	-0.611		
NAI		0.885	
GAI		0.884	
CROPINTN		0.795	
CROPCONC		0.737	
GWIPCTOT			0.775
PCKHHYV			0.773
GWSWR			0.675
MEANGWD			0.527

Extraction Method: Principal Component Analysis. Rotation Method: Varimax with Kaiser Normalization. Rotation converged in 5 iterations. * % of total variance explained = 70.4. Scores below 0.5 have been suppressed.

Table A3: Rotated Component Matrix: Factor Extraction (Rabi Rice Crop)

	Factors			
	CLIMATIC	**HYDROCLIM**	**AGINTENS**	**TECHDIFF**
Eigenvalue after rotation	4.1	3.5	3.2	2.3
% Contribution to total variance after rotation*	24.1	20.4	18.5	13.3
DYRAIN	0.943			
SDDRYRAIN	0.911			
SDMRFDRY	0.911			
ETRAINDRY	-0.856			
SDANRAIN		0.879		
SDMEFFR		0.846		
ANRAIN	0.539	0.759		
SDETDRY		-0.681		
USRECHARGE		0.627		
NAI			0.853	
GAI			0.841	
CROPINTN			0.819	
CROPCONC			0.789	
GWIPCTOT				0.842
GWSWR				0.755
MEANGWD				0.594
PCRABIHYV			0.532	0.545

Extraction Method: Principal Component Analysis. Rotation Method: Varimax with Kaiser Normalization. Rotation converged in six iterations. * % of total variance explained = 76.3. Scores below 0.5 have been suppressed.

Table A4: Rotated Component Matrix: Factor extraction (Annual Rice Crop)

	Factors			
	CLIMATIC	**HYDROCLIM**	**AGINTENS**	**TECHDIFF**
Eigenvalue after rotation	5.3	5.1	2.9	2.5
% Contribution to total variance after rotation*	25.1	24.4	14.0	12.1
SDMRFWET	0.936			
SDWETRAIN	0.933			
SDANRAIN	0.880			
WETRAIN	0.803			
ETRAINWET	-0.742			
ANRAIN	0.681	0.673		
SDMEFFRWET	0.538			
SDMRFDRY		0.922		
SDDRYRAIN		0.922		
DYRAIN		0.903		
ETRAINDRY		-0.826		
USRECHARGE		0.637		
SDETDRY	-0.504	-0.553		
NAI			0.904	
GAI			0.882	
CROPINTN			0.771	
CROPCONC			0.730	
PCHYVALL				0.853
GWIPCTOT				0.804
GWSWR				0.731
MEANGWD				0.519

Extraction Method: Principal Component Analysis. Rotation Method: Varimax with Kaiser Normalization. Rotation converged in 5 iterations. % of total variation explained = 75.8. Scores below 0.5 have been suppressed.

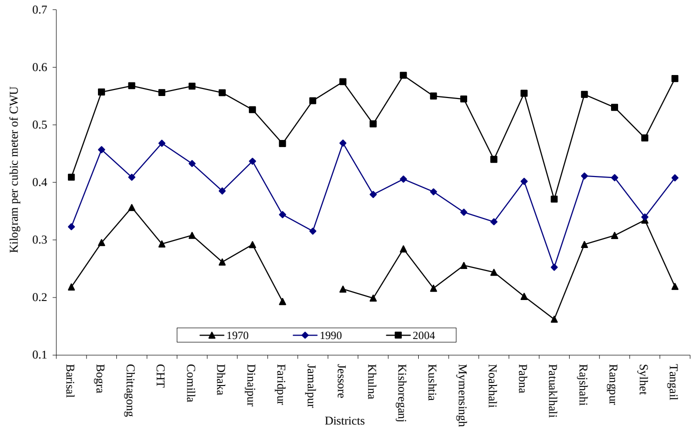

Figure 1A : Kharif crop

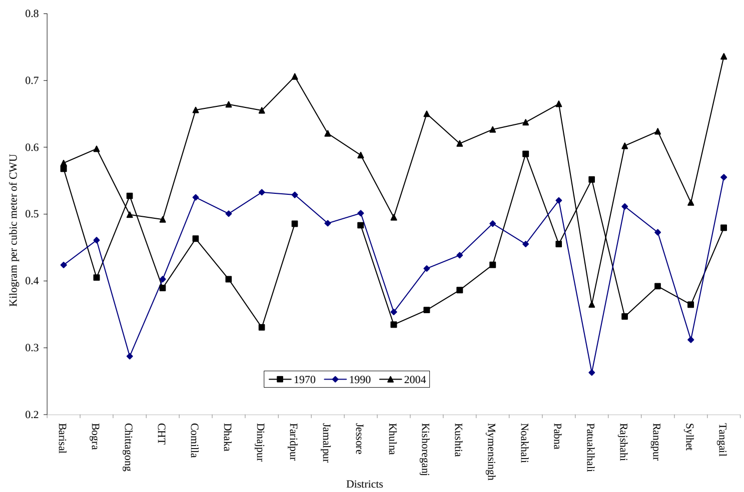

Figure 1B: Rabi crop

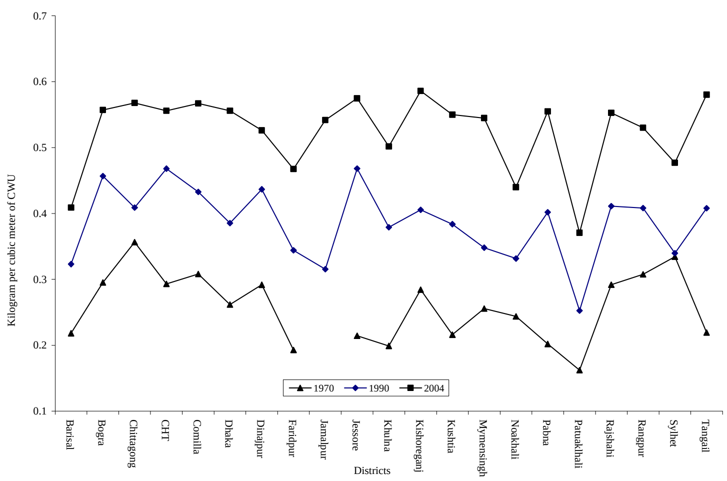

Figure 1C: Annual crop

Figure 1: Levels of water productivity of kharif, rabi and annual rice crops for Bangladesh districts for selected years (1970, 1990 & 2004).

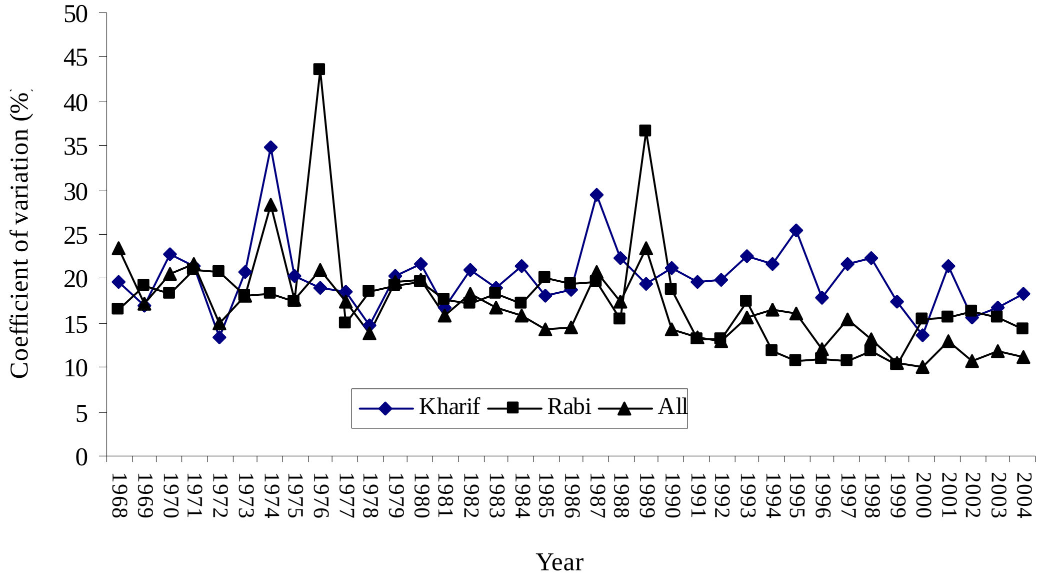

Figure 2: Trends in coefficients of variation in water productivities of kharif, rabi and annual rice crops across Bangladesh districts, 1968-2004.

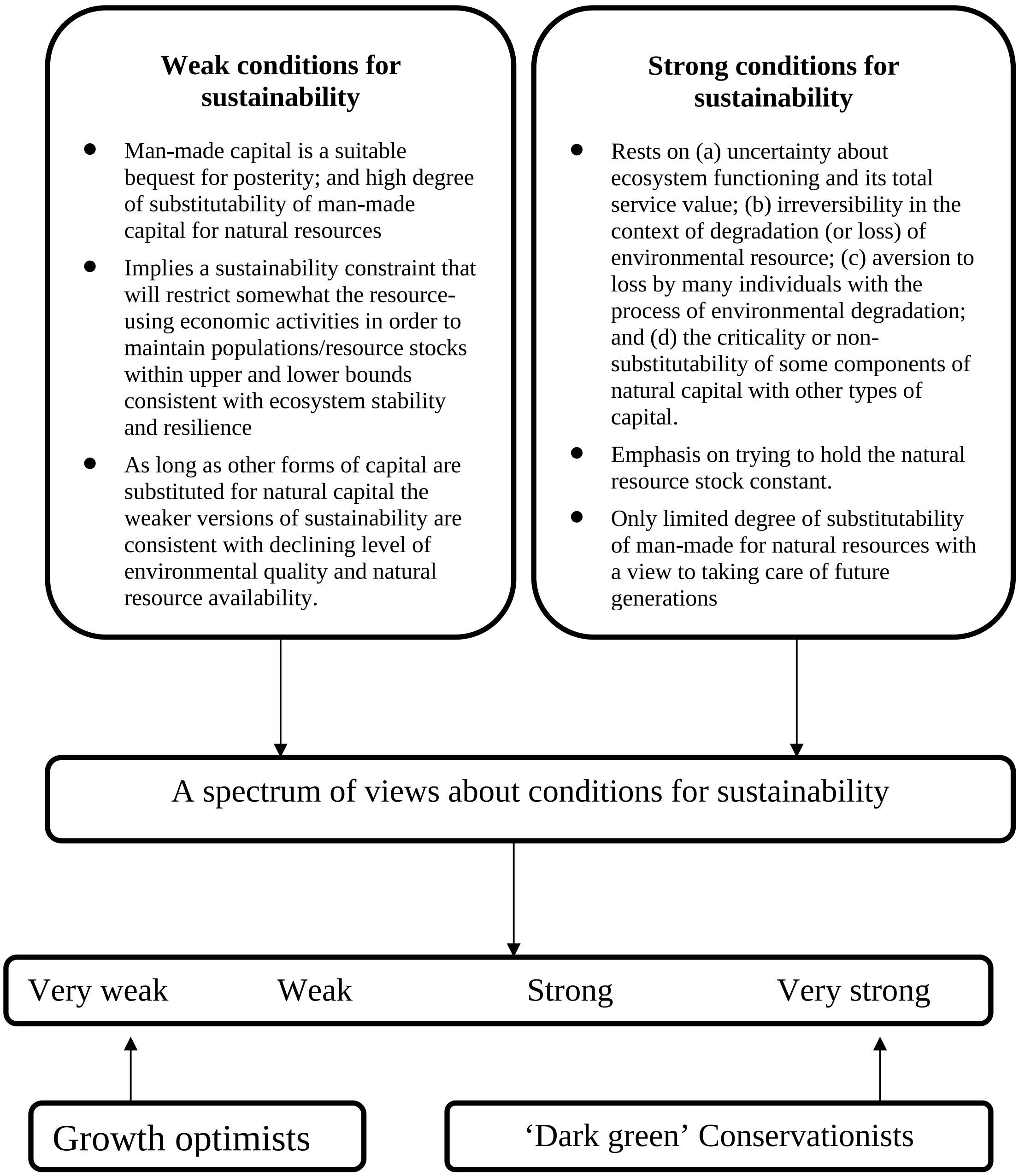

Figure 3: Weak and strong conditions for sustainability and spectrum of views about these conditions (Adapted from Pearce 1993; Turner et al 1994; Alauddin 2004).

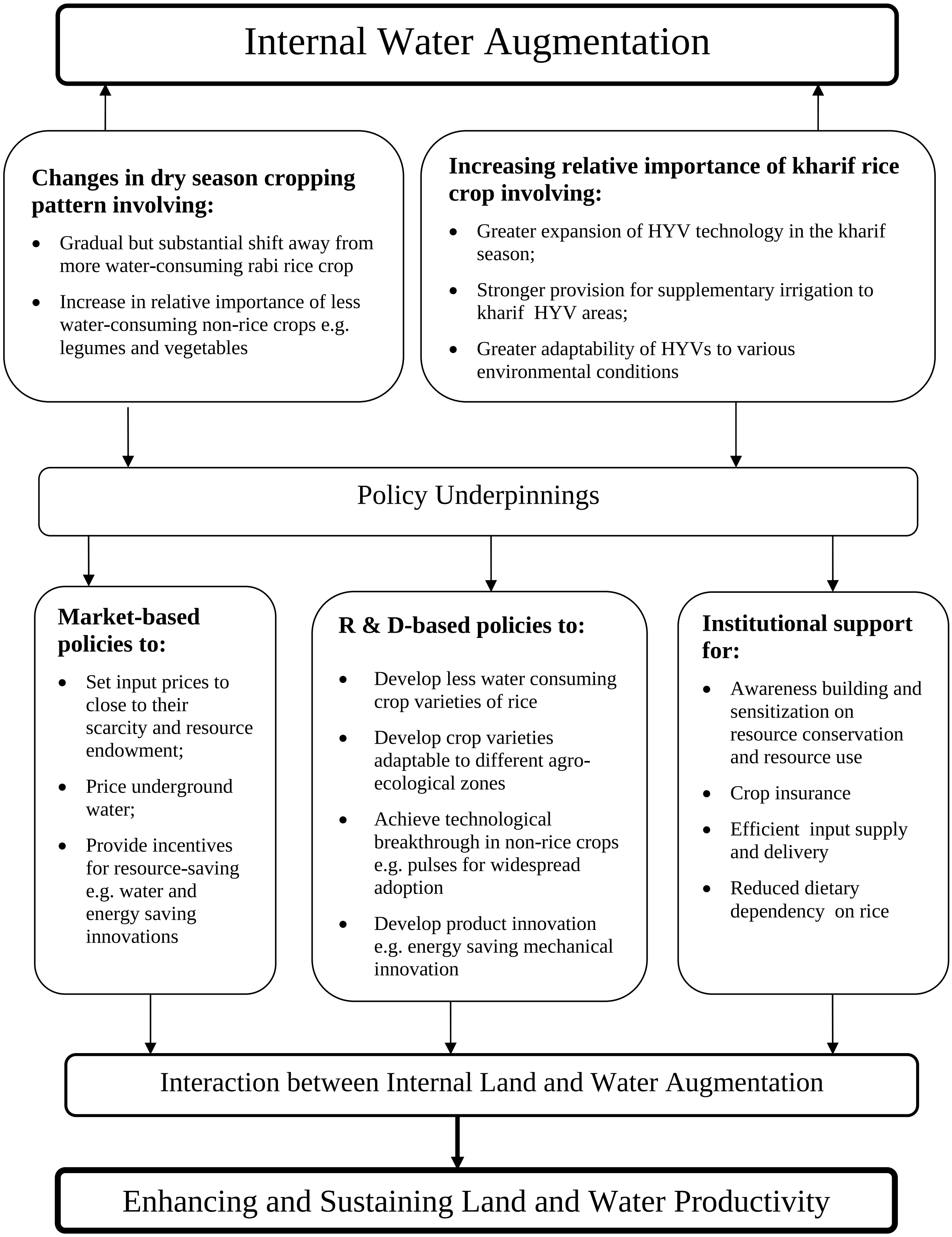

Figure 4: Sustaining agricultural intensification and productivity: Policy options