Irrigation water productivity in Cambodian rice systems*

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Abstract

In the context of increasing competition for water, knowledge of the marginal productivity of water is crucial in determining its optimal allocation between users. Using primary, plot level panel data, this paper estimates the marginal productivity of water from supplementary irrigation in lowland rice systems in Cambodia, taking into account farmer and plot heterogeneity as well as self-selection of supplementary irrigation. Our estimates indicate a range of elasticity for rice output with respect to water inputs between 0.057 and 0.069 for wet season production, and an estimate of 0.125 in the dry season, substantially lower than previous estimates based on either aggregate or trial data. We discuss the policy implications of these results, in particular with respect to the utility of demand management policies and the challenges they pose to the decentralization of water management to Water Users Groups that are meant to be financially independent.

1 Introduction

Globally, population growth, rising incomes and urbanization are increasing the demand for water from the household and industrial sectors (Strzepek and Boehlert, 2010). Developing countries are expected to experience an increase in non-agricultural demand for water of 100% between 1995 and 2025 (Turner et al., 2004) and, for the first time, absolute growth in non agricultural water consumption is greater than absolute growth in agricultural water consumption (Rosegrant, Cai, and Cline, 2002). Simultaneously, and for the same reasons, there is an increasing demand for food that is resulting in greater demand for water for agriculture. Heightened demand from the household, industrial and agricultural sectors is increasing the competition for water and this increased competition, coupled with concerns about national food security, has lead to growing interest in irrigation as a way to increase national production, especially given the increased uncertainty regarding the possible impacts of climate change on water availability (Bank, 2006)

Each of these drivers of demand (population growth, rising incomes and urbanization) is present in Cambodia. The Cambodian population is expected to increase from the current 14.2 million to between 20.4 and 27.4 million by 2050 (UNPD, 2008, ADB, 2010b), while simultaneously experiencing a strong record of economic growth, that averaged 9.1% between 1998 and 2008 (ADB, 2010a). Increases in per capita income and urbanization are also expected (UNPD, 2007), and the resulting increase in the demand for food is estimated to be between 109% and 206% from their year 2000 levels (Hoanh et al., 2003). If this increase in demand is to be satisfied by domestic production, greater pressure will be placed on agricultural resources, including water for agricultural production.

Finally, water management may become more important in the context of climate changes, in particular in the way that it may impact on the Mekong, which drains 86% of the land area of Cambodia (Dore, 2003) and provides 60% of the water for the its main agricultural region, the Tonle Sap plains (Sarkkula and Varis, 2009). While changes in climate are expected to increase the overall flow of the Mekong by 4.3%, this increase will be concentrated in the wet season (with an expected increase in flow of 5.14%), with a reduction in the dry season flow of 2.18%. Additionally, Cambodia will become slightly warmer, and rainfall increasingly variable, though similar on average for the first half of this century, thus making irrigation even more important to rice production (Keskinen et al., 2009). Additionally, and for the same reason, water availability in Cambodia will also be impacted upon by the construction of dams in the Mekong River Basin: there will be less water in the wet season and more water in the dry season (Lamberts, 2008, Sarkkula and Varis, 2009).

As in many other countries, agriculture is the main water user in Cambodia. Nesbitt, Johnston, and Solieng (2004) puts water withdrawals for agriculture in the lower Mekong basin at 80-90% of total abstractions, slightly lower than the official estimates, that put agriculture as being responsible for 95% of water withdrawals (MOWRAM, 2009).

The effect of irrigation on rice production is of particular significance to Cambodia as 30.1% of the Cambodian population lives in poverty (ADB, 2010b) (ADB 2010b), and irrigation has been shown to impact directly as well as indirectly on poverty. Irrigation helps the poor via greater yields and lower risk of crop failure (Hussain and Hanjra 2004), which in turn boosts income and employment opportunities whilst increasing options for crop diversification (Hasnip et al 1999). More broadly, heightened rice productivity increases food security and allows a greater diversification of employment of land and labor endowments (Hossain and Fischer 1995). Increased yields can benefit the urban poor by helping to prevent price rises associated with restricted supply (Turner et al 2004). Furthermore, the benefits of water use in agriculture may be much greater at a national level than the farm level, as found by Hussain et al (2007) with their estimate of agricultural water values ranging from US$0.04/m^3 at the farm level to US$0.22/m^3 at the national level for agricultural water in the Indus valley in Pakistan.

Water in Cambodia is owned by the state (Jennar 1995), and the Cambodian Governments “Rectangular Strategy” (Royal Government of Cambodia 2004) emphasizes the importance of increased agricultural productivity, to which water management is central. Some Cambodian farmers pay monies to Farmer Water Users Committees (FWUC) but the roles and responsibilities of these committees are often unclear, and 91% of water user fees imposed by the FWUC are not paid in the areas assessed in this study (CDRI 2009). Awareness of the marginal productivity of water on rice production can help inform water policy into the future by informing cost benefit analyses of the expansion of irrigation infrastructure, assessment of different policies to price water to achieve particular policy objectives such as cost recovery or increased water productivity (Molle and Berkoff 2007) and the pursuance of market driven approaches to irrigation management which can provide signals of relative scarcity (Young 2005).

The paper proceeds as follows. Section 2 identifies key aspects of the existing literature on water productivity in rice systems, with a particular emphasis on the lower Mekong. Section 3 describes the data. Section 4 discusses the empirical approach used in this study (section 4.1), and presents the empirical estimates (sections 4.2 and **??**). We also present some possible extensions of the analysis to issues such as inter-sectoral water allocation and the setting of water fees (section). Section 5 concludes.

2 Water productivity: an analysis of the ex ante literature

Increased competition for water brings with it an increased need to quantify its value in different uses. The existing literature provides several measures of water productivity, that is, of the ratio between output and water use. These quantities have been defined in a variety of different ways, each of which provides information that may be adequate to answer different questions (Cook et al 2006) although it seems fair to say that data availability has also played a role in determining the approach followed. In Table 1 we present a brief summary of previous studies that tried to quantify water productivity, with a particular emphasis on (but not limited to) South East Asian countries.

The first conclusion is that water productivity has been evaluated at different scales, from country to plot level. This is important for two reasons. Firstly, the scale of assessment changes the definition of water used and, with it, the value of water productivity, a point noted by Hafeez et al (2007): larger scales of assessment are generally associated with higher levels of water productivity. Secondly, different outcomes are relevant to different stakeholders, at different levels (Kijne et al 2003).

The second conclusion from the variety of studies listed in Table 1, is that a variety of ways of defining output and input has been used, a point noted by others (Kijne et al 2003). Output is most commonly defined in terms of physical quantities (especially in studies that focus on one crop, usually staples) or some measure of value, either gross or net of input costs (in studies that deal with agricultural production without focusing on one crop). More interestingly, because it reflects more clearly the data limitations and the assumptions regarding the importance of agriculture, a variety of measures of water input have been used, including gross water inflows, precipitation, irrigation inflows and actual and evapotranspiration.

It is clear from the studies listed that a focus on water use as quantified by different measures of evapotranspiration (actual, as in Bastiaanssen and Zwart 2006; potential, as in Goto et al 2008; and reference, as in Allen et al 1998) dominates the existing knowledge. However, only a small part of this is literature considers the lower Mekong basin, and an even smaller considers Cambodia. The use of these measures carries with it one important limitation, as it is often based on data from experimental stations or greenhouse/pot experiments, which may not reflect actual production conditions.[1]

Finally, these studies differ on their assumption regarding the importance of different flows: particularly important from a policy perspective, several (for example, Mainuddin and Kirby (2009), Haddeland et al (2006)) assume that irrigation, namely during wet season, in not important for rice production, focusing instead on the contribution of rainfall.

[1] Other studies (for example Bouman and Tuong (2001)) use experimental methods to quantify water productivity under different production scenarios, some of which may not be practiced in the field.

3 Data

The data used in this study was collected as part of a wider study addressing water management in the Tonle Sap watershed, in Cambodia. The characterization of the 17 schemes included in this study is presented in CDRI (2010). Of these, 10 schemes were selected to represent the range of degrees of water availability in the watershed, as proxied by their postion along the stream[2]. The characteristics of these schemes are presented in table 2.

In each irrigation scheme, 30 households were selected to be interviewed. Because of the relatively small sample size, households were selected with the help of village heads to represent a range of wealth and plot characteristics typical of each scheme. These households were interviewed in mid-2008, through the fielding of a questionnaire that was designed to capture information on variables that are more or less constant through time: household composition, characteristics of the head of the household (gender, age, education), plot characteristics and assets. Some of these variables are presented in table 3.

Households are relatively large (close to 6 people, on average), with almost 1/3 of the members being classified as dependents[3]. Most of the household heads are male, and only 5% of them completed primary schooling (or above). Turning to assets, it is important to notice the relatively large importance of livestock (on average, households own almost 2.5 TLU[4])

[2]Defined here, simply, as characterized by upstream, midstream and downstream.

[3]That is, aged over 65 years old or less than 15 years old.

[4]A TLU (or Tropical Livestock Units) is a measure that allows for the aggregation of different animal species, weighted according to their energy requirements. In South East Asia, 1 cow=0.8 TLU.

and the small importance of some mechanical equipment, in particular small tractors, that are owned by only 2% of the respondents[5]. It also seems important to notice the large variability in asset ownership within the sample: both with respect to overall livestock ownership and mechanical capital, the standard deviation is greater than the average.

This first questionnaire was followed by a different questionnaire, fielded after each season, that focused on changes in household composition and on decisions related to income generation (including farm and non-farm production) as well as other sources of income (transfers) and production shocks. Some descriptive statistics are presented in table 4, for each of the seasons for which we have data: 2008 and 2009 wet seasons and the 2009-10 dry season.

There are three main comments regarding the values presented in this table. The first is that, because the unit of observation is the plot, the number of observations in table 4 does not make it evident the extent of attrition between the first, household centered, questionnaire and the questionnaires fielded after each season. Nonetheless, the reduction in the number of households being interviewed is relatively important, with 64 households not being interviewed in the survey fielded during the 2008 wet season. Although there was no significant reduction in the the number of households in subsequent rounds[6], this still corresponds to an attrition rate of 21%, raising the possibility that the subsample for which we have production data is statistically different from the original sample. To confirm whether this was in fact the

[5]No household owns more than 1 small tractor

[6]We were able to interview 235 households during the 2008 and 2009 wet seasons and 218 households during the 2009-10 dry season.

case, we performed a series of t-tests of differences in mean values of variables relating to wealth, demographics and observable plot characteristics between households included in the second and the first surveys, with the null hypothesis of no difference between the mean values of different surveys. We could never reject the null hypothesis.[7]

The survey module used to ask about production data, and this is the second comment, was designed to closely follow the module used in the World Bank Living Standards Measurement Surveys (Reardon and Glewwe, 2000). This module, however, does not attempt to collect data on water use, a matter that is of central importance in this study. For that reason, it is worth explaining, in more detail, how we obtained information on water use at plot level. Finally, table 4 makes clear the different seasonal role of irrigation in the Cambodian context: 46% of the plots used irrigation water during wet season in both 2008 and 2009, a clear evidence that such practice cannot be ignored (as previous studies, listed in table 1 have done) but also of its supplementary character during wet season. On the other hand, during the 2009-10 dry season, and as expected, virtually no production is feasible without irrigation: 83% of the plots that registered any production used irrigation. That said, it is also clear, from both the information in tables 2 and 4, that the area under production during dry season is dwarfed by the area under production in wet season. These observations, and what they reflect about the production decisions of rice farmers in the surveyed schemes, carry important implications regarding the econometric estimation of this technology, to which we now turn.

[7] The results are omitted due to space but are available from the authors upon request.

4 Empirical approach and estimates

4.1 Econometric model

In order to estimate the contribution of irrigation water to rice production, we proceed by estimating a Cobb-Douglas production function of the form

$$Y_{it} = A_i \, W_{it}^{\beta} \, X_{it}^{\theta} \, e^{\lambda \, Z_{it} + \mu \, T + \varepsilon_{it}} \tag{1}$$

which, taking logs on both sides of the equation, can be rewritten as

$$lnY_{it} = A_i + \beta \, lnW_{it} + \theta \, X_{it} + \lambda \, Z_{it} + \mu \, T + \varepsilon_{it} \tag{2}$$

where Y is rice yield, W is irrigation water, X is the set of other inputs used, Z is a set of shocks and the subscripts i and t represent plot and time, respectively. We account for common seasonal effects through a time fixed effect, T. Finally, ε is statistical error and, in estimating equation 2, we assume that

$$\varepsilon_{it} \sim N(0, \sigma^2) \tag{3}$$

$$E(\varepsilon_{it}, \varepsilon_{jt}) = 0 \text{ if i} \neq \text{j} \tag{4}$$

$$E(\varepsilon_{it}, \varepsilon_{jz}) = 0 \text{ if t} \neq \text{z} \tag{5}$$

where equations 4 and 5 formalize the assumptions that, controlling for the exogenous variables, the error term is not correlated through space or time.

In equation 2 we assume that the Cobb-Douglas is an adequate functional form to represent the relation between output and conventional inputs. Other, more flexible functional forms (namely translog) were estimated but we were not able to reject the hypothesis that the additional terms were not jointly statistically significant and, for that reason, we only report the Cobb-Douglas results. The specification of equation 2 takes advantage of repeated observations at plot level to account, through the estimation of a plot specific intercept A_i, for unobserved plot heterogeneity and, given that land markets are virtually non-existent, farmer heterogeneity [8].

One problem with estimating equations such as 2, in log form, is how to deal with zero values in the original observations. In this case, we followed Battese (1997) solution and replaced the logged value also as 0 but included a set of dummy variables that account for this arbitrary decision.

When estimating equation 2, we must also address the possibility that irrigated plots are systematically different from those which are not, with "better" plots being irrigated while others may not be seen to be warrant the extra effort associated with supplementary irrigation. In short, the decision to use irrigation water during the wet season, even after controlling for input use and shocks, would still reflect unobserved heterogeneity. In this case, the assumption of normally distributed errors (equation 3) would not hold and the effect of irrigation water on rice output could be overstated.

Heckman (1984) has shown that it is possible to correct for this problem by first estimating the probability of each plot to receive supplementary irrigation through a probit model of the form:

[8] Plots are not usually rented out or in and, if they were, they would not be observed, as the unit of the survey was the household

$$I(W_i > 0) = \Phi(X_i) \tag{6}$$

This first stage regression allows us then to estimate the statistic $\frac{\phi}{\Phi}$, also known as the Inverse Mills Ratio (IMR) which can be interpreted as the likelihood that plot i will be irrigated. We can then estimate a second stage, of interest, as:

$$lnY_i = \beta\, lnW_i + \theta\, X_i + \lambda\, Z_i + \alpha IMR_i + \varepsilon_i \tag{7}$$

that is a modification of the model specified in equation 2 in three important aspects. Firstly, through the inclusion of the IMR_i variable that indicates the likelihood of plot i receiving supplementary irrigation, we can correct for self-selection into supplementary irrigation.

Secondly, through the absence of the subscript t from equation 7. As noted, the use of Heckman's correction procedure requires the estimation of the IMR_i through a probit model but, due to the incidental parameter problem, there is no estimator of such models that allows for the inclusion of fixed effects. Finally, and because of our inability to take advantage of repeated plot observations to account for unobserved heterogeneity, we need to expand the vector X to include other plot characteristics for which we have information (slope, soil type, ...) and that are both time invariant and possibly correlated with the amount of water used by farmers.

4.2 Empirical estimates: wet season

The empirical estimates for equation 2, during wet season, are presented in Table 5. Of the variable inputs, household labor and fertilizer seem to be the most significant constraints, and relaxing them would positively impact on productivity. The estimate associated with irrigation water is relatively low: a 1% increase in water use leads to a 0.057% increase in rice output. Because these estimates were obtained using a fixed effects specification, we account for all those variables which can be considered to be constant trough time (such as farmer ability, soil type and slope), although not for the possibility that farmers selectively irrigate plots.

We address that problem by estimating a Heckman selection model, using maximum likelihood. The estimates, for the 2008 wet season, the 2009 wet season and then for the entire sample are presented in tables 6, 7 and 8, respectively. As the identifying instrument, we used changes in the dependency ratio (as changes in the number of dependents would, presumably, lead to changes in the plots used for production but, given that dependents do not contribute with labour, would not influence production directly) and the position of the scheme along the watershed (that, conditional on water used in the plot, should not matter). The significance of the estimate of ρ in all three models signals that there is in fact some selectivity in the decision of which plots are irrigated. However, the estimates of water productivity do not seem to be significantly affected by this fact: if we consider the estimates presented in table 8, which include both wet seasons and, as such, are more easily compared with the results presented in table 5, the estimate of water productivity is now 0.069, quite similar (and statistically identical) to 0.057.

The fact that they are slightly above our fixed effects estimates is, however, a bit puzzling and suggests that the estimates of water productivity may be biased, as they would reflect the effect of both water and other correlated (but not included) variables such as plot characteristics, for example. In an effort to test whether this is the case, we re-estimated the Heckman selection model using data for both seasons and adding extra control variables, namely soil type and slope and distance to the plot from the homestead. The results are presented in table 9 and, although they confirm our suspicion, the changes are minimal: the estimate of water productivity is now 0.066, almost identical to our previous results. In conclusion, although farmers seem to be selectively choosing which plots to irrigate (as we would expect), conditional on all other variables for which we have information, this does not seem to matter much for our estimates of water productivity. For that reason, we will focus the rest of the discussion in this section on the estimates presented in table 5.

It is interesting at this point to examine how our estimates compare with those in the literature presented in section 2. We start by noticing that the estimates presented in this paper differ fundamentally from previous estimates of water productivity. Given that our estimates are elasticities, both average and marginal productivity of water can be estimated for the *entire* range of water input values and, in this sense, our results are superior to previous estimates of water productivity which are applicable to only a limited range of water input values. This raises the natural question: what is the overlap between the water use implied by the ex-ante estimates, and the use of water in the field, as shown in our data? We address this question by relating existing estimates of average productivity with the frequency of water input values in our data which could correspond to these average productivities, given our estimates.

These comparisons are summarized in table 10, and their meaning can be understood by looking, for example, to the average productivity values recorded by Mainuddin and Kirby (2009) for total inflow (assuming negligible irrigation volumes) in Cambodia. The values of average productivity reported in this study, between 0.110 kg/m^3 and 0.242 kg/m^3, correspond to a range of water input volumes between 1500m^3 and 3500m^3, which accounts for 9.1% of the water volume used by the farmers that we surveyed. Similarly, the average productivity presented by Loeve et al (2004), for irrigation water at the plot level in China, correspond to water volumes that, overall, account for approximately 34% of the water used by farmers in this study and Cabangon et al (2002) approximately 8.6%. In short, the ex-ante literature seems crucially limited in explaining water productivity in the Cambodian context, as shown by the limited overlap between real water use by Cambodian farmers and the associated levels of water productivity and, most importantly from a policy perspective, they seem to substantially overstate real (farmer) water productivity.

4.3 Empirical estimates: dry season

Given that it is not possible to produce during the dry season without irrigation, and that we only have one round of data for production during the dry season (the 2009-2010 dry season), the approach to consistently estimate water productivity in the dry season has necessarily to be different from the one used in the previous section. In table 11, we present the ordinary least squares estimates of the production function when we include additional controls for plot characteristics. It is immediately obvious that the estimates of water productivity are considerably lower than the estimates obtained during wet season and are not statistically significant at the usual levels of significance. These are unexpected results, given the importance of irrigation water during dry season, and most probably reflect an incorrect specification of the statistical model.

One alternative to this specification is possible if we are willing to assume that, controlling for other inputs, there is no significant technological difference between wet and dry season production. We are then able to take advantage of the existence of several rounds of data to adequately control for plot and farmer fixed effects, as is done for the wet season. The estimates of this model are presented in table 12 and indicate an elasticity estimate of 0.125, that is statistically significant at the 10% level. Under the assumption that rice technology does not vary across seasons, irrigation water productivity in the dry season is roughly twice of the wet season estimate which is, intuitively, more plausible.

As before, we are interested in comparing these estimates with those of the existing literature, following the approach detailed above, in particular comparing the estimates presented in table 12 with the existing literature. These comparisons are also presented in table 10. As in the wet season, the dry season estimates presented in this paper differ fundamentally from previous estimates of water productivity and it is possible to conclude that those substantially overestimate water productivity by Cambodian farmers.

4.4 Possible extensions of the analysis

Knowledge of the average and marginal economic value as estimated in this study can be combined with various prices (namely farm gate, provincial market or international) to give average economic values for water, akin to Phengphaengsy and Okudaira (2008) as well as marginal economic values. Without wanting to assume such prices, we can still estimate a demand curve, where the price is expressed in kg rice/m^3. This is represented in figure 1 for the entire sample. The main point to notice is the wide range of water use for which its marginal productivity is relatively low: uses above 1 million cubic meters have a marginal productivity smaller than 0.01 kg rice/m^3. Knowledge of water productivity in other uses (for example, fisheries) could guide a decision to privilege the development of other sectors.

Equally interesting is to use the result of figure 1 to evaluate the capacity that Water User Groups (WUG) have to raise revenue (and, potentially, be financially sustainable) through increases in water fees. We do that by assuming that farmers, if charged more than the marginal productivity of water, will stop using this input. The decision of the WUG is then to raise revenue by setting the water fee, knowing that some farmers will stop using supplementary irrigation if the fees rise above their on-plot valuation of water. The results of this exercise are shown if figure 2, when revenue is expressed in tonnes of rice (knowing the price of rice it is then a simple matter to convert this values to monetary values) and the water fee is expressed, as above, in kg rice/m^3. Clearly, if the fee is 0, the WUG raises no revenue, hence the curve intersects the origin of the two axis. Up to a relatively small amount (0.012 kg rice/m^3), revenue increases as fee increases given that farmers are being charged a higher value for their water but few find it unworthy to keep using irrigation water. However, above that value, fee increases lead to actual revenue decreases. Clearly, policy makers contemplating the use of water fees to fund WUG clearly need to take this type of behavior in assessing the feasibility of these policy options.

5 Conclusion

Increasing competition for water both within and between sectors will necessitate a heightened awareness of marginal benefits of water in its competing uses if optimal allocations of water are to be achieved. This paper has estimated the marginal productivity of water in its largest use in Cambodia, the irrigation of rice. This paper utilizes plot level, panel data to estimate elasticities between 0.058 and 0.082 in the wet season, and 0.125 in the dry season. Fixed effects regressions were used to account for inputs into the production process which can be considered to be constant, such as plot slope, soil type and characteristics of the head of the household. Heckman regressions were used to correct for self selection of plots for irrigation.

Comparisons of the results presented in this paper with those of previous research demonstrate the limitations of these previous estimates. This is an implication of the restricted range of water input values for which previous estimates are applicable (in relation to the water input values recorded in this study). Conversely, the estimates presented in this paper allow average and marginal productivities of water to be calculated over the full range of water input values. Further research into the marginal productivities in other significant uses of water in Cambodia will be crucial to take full advantage of the estimates included in this paper, through the elucidation of opportunity costs of water allocated to the irrigation of rice.

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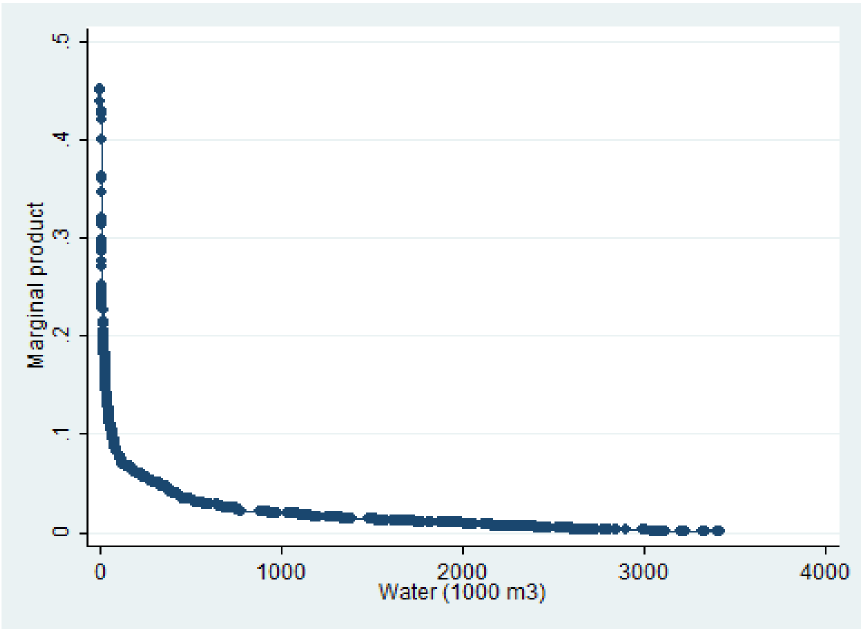

Figure 1: Demand curve

Table 1: Water productivity: ex-ante estimates

Study	Country	Period	Irrigation	Water measure	Scale	Water productivity
Hafeez et al (2007)	Philippines (dry season)	2000-01	Included	Gross	1 scheme (1500-18,000 ha)	0.05-0.18 kg/m^3
Mainuddin and Kirby (2009)	Laos Thailand Cambodia Vietnam	1993-2004 1995-2003 1993-2003 1995-2004	Excluded	Rainfall + surface + underground	provincial	Laos: 0.20-0.49 kg/m^3 Thailand: 0.20-0.30 kg/m^3 Cambodia: 0.11-0.24 kg/m^3 Vietnam: 0.30-48 kg/m^3
Phengphaengsy and Okudaira (2008)	2006-07 (dry season)	Laos Thailand Cambodia	Included	rainfall +irrigation + surface + underground	scheme	Laos: $0.09\$/m^3$ Thailand: $0.12\$/m^3$ Cambodia: $0.04\$/m^3$
Loeve et al (2004)	2000	China	Included	Gross Irrigation 	Sub-basin Plot Sub-basin Plot	0.32kg/m^3 0.67kg/m^3 2.19 kg/m^3 1.65 kg/m^3
Cabangon et al. (2002)	1988-1994 (dry and wet seasons)	Malaysia	Included	Irrigation	Plot	Dry: 1.48 kg/m^3 Wet: 0.62kg/m^3

Table 2: Scheme characteristics

Province	Catchment	Scheme	Construction year	Rehabilitation year	FWUC year	Population	Cropped area Wet	Cropped area Dry	Stream position	Tonle Sap floodplain
Pursat	Pursat	Damnak Ampil	1978	2006	2005	93,800	2670	1230	Upstream	No
Pursat	Pursat	Kampang	2004	–	2004	5800	2000	1570	Midstream	No
Pursat	Pursat	Wat Leap	1960	2003	2003	13,100	3050	170	Downstream	Yes
Kampong Chhnang	Chrey Bak	Pok Paen	1969	2005	2005	4000	1980	0	Upstream	No
Kampong Chhnang	Chrey Bak	Svay Chek	1973	2005	–	6100	1900	0	Midstream	No
Kampong Chhnang	Chrey Bak	Tang Krasang	1976	2001	pre 2007	8200	2600	0	Midstream	No
Kampong Chhnang	Chrey Bak	Trapeang Trabek	1987	1991	2001	5800	2340	1220	Downstream	Yes
Kampong Thom	Chinit	Chinit	1978	2007	2002	20,800	3700	520	Upstream	No
Kampong Thom	Chinit	O' Svay	1975	1998	–	11,500	2540	0	Midstream	No
Kampong Thom	Chinit	Rolous	1960s	2004	2005	22,100	13600	690	Downstream	Yes

Table 3: Household characteristics

Variable	Definition	Number of observations	Mean	Standard deviation
Household size	Number of people in the household	299	5.74	2.15
Dependency ratio	Percentage of dependents	299	36	24
Household head:				
Age	Age, in years	292	46.21	15.19
Male	Percentage of household heads who are male	292	73	
Primary schooling	Percentage of household heads who completed primary schooling	286	5.6	
Assets:				
Livestock	Ownership of livesctok, in TLUs	299	2.47	3.78
Mechanical water pump	Number of mechanical water pump owned by household	299	0.28	0.56
Small tractor	Number of small tractors owned by household	299	0.02	0.14
Oxcart	Number of oxcart owned by household	299	0.69	0.53

Table 4: Production data

	wet season, 2008					wet season, 2009					dry season, 2009-10				
Variable	Obs.	Mean	S.D.	Min.	Max	Obs.	Mean	S.D.	Min.	Max	Obs.	Mean	S.D.	Min.	Max
Area (ha)	1017	0.52	0.88	0.002	11	1010	0.53	0.91	0.002	11	143	0.89	1.03	0.02	5
Irrigated area (ha)	621	0.54	0.90	0.003	10	606	0.55	0.95	0.002	10	136	0.87	0.99	0.02	5
Yield (kg)	1017	951	1852	0	27500	1010	867	2040	0	33000	143	2880	4282	0	23000
Irrigation Water (m^3)	467	3393	8126	5	99000	458	8355	105308	0.15	2248200	121	7190	10312	50	53640
Household labour (days)	1009	16.7	18.7	0.22	139	1001	17.4	20.6	0.22	275	138	24.6	23.2	2	142
Hired labour (days)	1009	27.8	62.9	0	200	1001	6.61	19.7	0	305	138	6.6	15.2	0	120
Fertilizer (N, kg)	1009	7.23	31	0	618	1001	9.54	50	0	1125	143	29.1	43.6	0	338
Shocks:															
Disease	1017	0.17				1010	0.14				143	0.42			
Pest	1017	0.45				1010	0.41				143	0.79			
Flood	1017	0.07				1010	0.17				143	0.04			
Drought	1017	0.10				1010	0.21				139	0.30			

Table 5: Estimation results : fixed effects, wet season, 2008 & 2009

Variable	Coefficient	(Std. Err.)
Land (ln)	0.118	(0.093)
Household labor (ln)	0.141*	(0.059)
Hired labor (ln)	-0.015	(0.038)
Seed (ln)	0.025	(0.029)
Nitrogen (ln)	0.135**	(0.041)
Phosphate (ln)	0.127**	(0.034)
Water (ln)	0.057*	(0.028)
Disease	-0.004	(0.053)
Pest	0.027	(0.045)
Flood	-0.427**	(0.078)
Drought	0.079	(0.058)
Wet season 2008	0.247**	(0.042)
Intercept	5.395**	(0.329)
N	1948	
R^2	0.184	
$F_{(16,1035)}$	8.489	

Significance levels : † : 10% $*$: 5% $**$: 1%

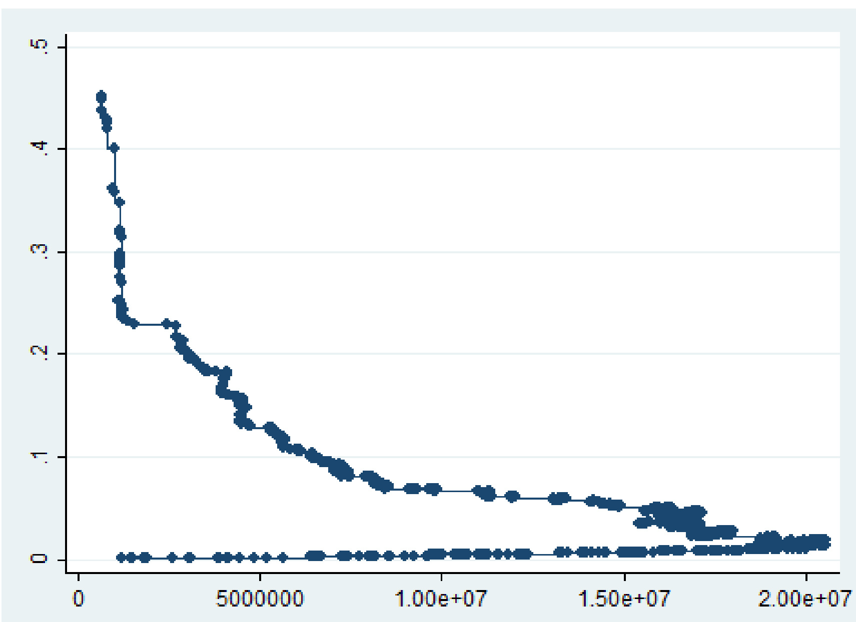

Figure 2: Total revenue curve

Table 6: Estimation results : Heckman correction, wet season 2008

Variable	**Coefficient**	**(Std. Err.)**
Equation 1 : Yield		
Land (ln)	0.458**	(0.046)
Household labor (ln)	0.102*	(0.041)
Hired labor (ln)	0.136**	(0.037)
Seed (ln)	-0.067	(0.104)
Nitrogen (ln)	0.071†	(0.043)
Phosphate (ln)	0.178**	(0.049)
Irrigation water (ln)	0.063*	(0.026)
Disease	0.163†	(0.084)
Pest	0.065	(0.060)
Flood	0.136	(0.124)
Drought	-0.012	(0.090)
Intercept	6.562**	(0.393)
Equation 2 : Irrigation water		
Change in dependency ratio, round 1	1.412	(1.019)
Upstream	0.042	(0.086)
Midstream	0.050	(0.078)
Intercept	-0.011	(0.065)
ρ	-1.373**	(0.136)
σ	-0.043	(0.062)
N	997	
Log-likelihood	-1218.119	
$\chi^2_{(15)}$	1141.802	

Significance levels : $\dagger$: 10% $*$: 5% $**$: 1%

Table 7: Estimation results : Heckman correction, wet season 2009

Variable	**Coefficient**	**(Std. Err.)**
Equation 1 : lnyield		
Land (ln)	0.396**	(0.048)
Household labor (ln)	0.117*	(0.047)
Hired labor (ln)	0.130**	(0.049)
Seed (ln)	0.093*	(0.041)
Nitrogen (ln)	0.039	(0.040)
Phosphate (ln)	0.353**	(0.052)
Irrigation water (ln)	0.075**	(0.027)
Disease	0.004	(0.090)
Pest	0.152*	(0.070)
Flood	-0.392**	(0.118)
Drought	0.128	(0.086)
Intercept	5.792**	(0.307)
Equation 2 : water1		
Change in dependency ratio, round 3	0.803	(0.579)
Upstream	0.242**	(0.082)
Midstream	0.245**	(0.074)
Intercept	-0.206**	(0.066)
ρ	-1.864**	(0.191)
σ	0.189**	(0.073)
N	975	
Log-likelihood	-1219.298	
$\chi^2_{(15)}$	1361.538	

Significance levels : † : 10% $*$: 5% $**$: 1%

Table 8: Estimation results : Heckman correction, wet seasons, 2008 & 2009

Variable	**Coefficient**	**(Std. Err.)**
Equation 1 : Yield		
Land (ln)	0.409**	(0.038)
Household labor (ln)	0.103**	(0.037)
Hired labor (ln)	0.131**	(0.032)
Seed (ln)	0.068*	(0.033)
Nitrogen (ln)	0.059†	(0.033)
Phosphate (ln)	0.289**	(0.039)
Irrigation water (ln)	0.069**	(0.022)
Disease	0.068	(0.062)
Pest	0.111*	(0.045)
Flood	-0.253**	(0.082)
Drought	0.125*	(0.062)
Wet season 2008	0.277**	(0.056)
Intercept	5.940**	(0.245)
Equation 2 : Irrigation water		
Wet season 2008	0.027	(0.032)
Change in dependency ratio, round 1	4.258**	(1.249)
Change in dependency ratio, round 3	2.053*	(0.956)
Upstream	0.139†	(0.072)
Midstream	0.138*	(0.069)
Intercept	-0.137*	(0.063)
ρ	-1.609**	(0.115)
σ	0.095†	(0.053)
N	1972	
Log-likelihood	-2455.214	
$\chi^2_{(16)}$	1616.376	

Significance levels : † : 10% * : 5% ** : 1%

Table 9: Estimation results : Heckman correction with additional control variables, wet seasons, 2008 & 2009

Variable	**Coefficient**	**(Std. Err.)**
Equation 1 : Yield		
Land (ln)	0.408**	(0.038)
Household labor (ln)	0.095*	(0.038)
Hired labor (ln)	0.138**	(0.032)
Seed (ln)	0.072*	(0.033)
Nitrogen (ln)	0.061†	(0.034)
Phosphate (ln)	0.280**	(0.041)
Water (ln)	0.066**	(0.021)
Disease	0.087	(0.061)
Pest	0.105*	(0.044)
Flood	-0.282**	(0.081)
Drought	0.138*	(0.063)
soil: kadeng	-0.153	(0.163)
soil: kasach	0.025	(0.175)
soil: robuykasach	-0.286†	(0.167)
flat	0.248	(0.157)
slight slope	0.064	(0.167)
moderate slope	0.014	(0.219)
Wet season 2008	0.258**	(0.056)
Time to plot (hours)	0.025	(0.019)
Intercept	5.918**	(0.258)
Equation 2 : water1		
Wet season 2008	0.021	(0.032)
Change in dependency ratio, round 3	1.825†	(0.933)
Change in dependency ratio, round 1	3.991**	(1.247)
Upstream	0.142†	(0.074)
Midstream	0.164*	(0.071)
soil: kadeng	0.238	(0.178)
soil: kasach	-0.195	(0.192)
soil: robuykasach	0.241	(0.186)
flat	-0.172	(0.178)
slight slope	0.044	(0.190)
moderate slope	-0.003	(0.234)
Time to plot (hours)	-0.041*	(0.020)
Intercept	-0.149†	(0.087)
ρ	-1.592**	(0.121)
σ	0.075	(0.055)
N	1966	
Log-likelihood	-2416.111	
$\chi^2_{(23)}$	1613.598	

Significance levels : † : 10% $*$: 5% $**$: 1%

Table 10: Comparison of results with existing literature

Study	Estimates (kg/m^3)	Wet season: Water use range (m^3)	Wet season: Water use (%)	Dry season: Water use range (m^3)	Dry season: Water use (%)
Mainuddin and Kirby (2009)	0.110-0.242	1500-3500	23.7	> 22500	11.9
Loeve et al. (2004)	1.65	Not in range		2500	3.3
Cabangon et al. (2002)	0.62 (wet) 1.48 (dry)	500	34	2500-3000	7.4
Hafeez et al (2007)	0.05-0.18	Dry season only		> 29000	4.9

Table 11: Estimation results : linear regression, dry season, 2009-10

Variable	**Coefficient**	**(Std. Err.)**
Land (ln)	0.492**	(0.104)
Household labor (ln)	0.047	(0.108)
Hired labor (ln)	-0.030	(0.068)
Nitrogen (ln)	0.555**	(0.139)
Phosphate (ln)	-0.001	(0.148)
Water (ln)	0.036	(0.043)
Intercept	6.212**	(0.676)
N	95	
R^2	0.82	

Significance levels : $\dagger$: 10% $*$: 5% $**$: 1%

Table 12: Estimation results : fixed effects, dry season, 2009-10

Variable	**Coefficient**	**(Std. Err.)**
Land (ln)	0.166†	(0.086)
Household labor (ln)	0.127*	(0.050)
Hired labor (ln)	0.005	0.034
Nitrogen (ln)	0.141**	(0.037)
Phosphate (ln)	0.122	(0.030)
Water (ln)	0.125†	(0.068)
Intercept	5.439**	(0.363)
N	2049	
R^2	0.58	

Significance levels : $\dagger$: 10% $*$: 5% $**$: 1%