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Valuing groundwater recharge through agricultural production in the Hadejia-Nguru wetlands in northern Nigeria

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Abstract

This study applies a production function approach to value the groundwater recharge function of the Hadejia-Nguru wetlands in northern Nigeria. The groundwater recharge function supports dry season agricultural production which is dependent on groundwater abstraction for irrigation. Using survey data this paper first carries out an economic valuation of agricultural production, per hectare of irrigated land. We then value the recharge function as an environmental input into the dry season agricultural production and derive appropriate welfare change measures. Welfare change is calculated using the estimated production functions and hypothetical changes in groundwater recharge and hence, groundwater levels. By focusing on agricultural production dependent solely on groundwater resources from the shallow aquifer, this study establishes that the groundwater recharge function of the wetlands is of significant importance for the floodplain.

JEL classification: Q10; Q25

Keywords: Production function approach; Valuation; Wetlands; Groundwater recharge; Ecosystem function

1. Introduction

The Hadejia-Nguru wetlands in northern Nigeria are formed by the floodwaters of the region's two principal rivers, the Hadejia and the Jama'are. The rivers exhibit ephemeral flow patterns with periods of no flow in the dry season (October–April). Almost 80% of the total annual runoff occurs in August/September. (Thompson and Hollis, 1995). During this period, waterlogged areas known as *fadamas* are formed and are important not only for fishing and agricultural activities, making these some of the most productive areas in northern Nigeria, but also for providing recharge to the underlying aquifers (Hollis and Thompson, 1993). Water from these aquifers is used for domestic consumption and for irrigation during the dry season.

A number of water diversion schemes have been constructed or are planned upstream of these wetlands. These schemes will divert floodwater away from the wetlands, reducing the annual flooding within the floodplain (Hollis et al., 1993). Barbier et al., (1993) and Barbier and Thompson (1998) have shown that the economic value of the wetlands in terms of floodplain agriculture and fishing, is signif-

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icant and will be affected by the construction of new dams and water diversion schemes. The economic value of the opportunity costs associated with diverting this water away from the wetlands has not been fully realised and incorporated into the development plans for this region. Hydrologists have noted that an important environmental function of these wetlands is in recharging the groundwater resources of the area (DIYAM, 1987; Thompson and Hollis, 1995).

The aim of this paper is to partially value the groundwater recharge function of the wetlands by applying the production function approach to analysing groundwater use in irrigated agriculture.[1] The groundwater recharge function is assumed to support dry season agricultural production dependent on groundwater abstraction for irrigation. Using survey data on agricultural production in the floodplain, this paper first carries out an economic valuation of agricultural production, per hectare of irrigated land. Following approaches advocated in the valuation literature (Ellis and Fisher, 1987; Mäler, 1992; Freeman, 1993; Barbier, 1994), we value the recharge function (through water input) as an environmental input in dry season agricultural production dependent solely on groundwater resources from the shallow aquifer. Two welfare change measures are derived and related to the recharge function of the wetland. Welfare change is then calculated using the estimated production functions and hypothetical changes in groundwater level.

2. Groundwater use in irrigated dry season farming

Agriculture in the Hadejia-Jama'are floodplain involves both dryland and *fadama* farming. These areas are flooded during the wet season and gradually dry out until they are flooded again during the next wet season. Floodplain activities have adapted to make use of the floodwaters and the *fadamas* in an ingenious way, taking advantage of the wetland's resources for grazing, agriculture and other economic uses.

[1] Throughout this paper, irrigated agriculture refers to irrigation with groundwater pumped up from the shallow aquifer with the use of small tubewells. Domestic water consumption within the wetlands is also dependent on groundwater resources, see Acharya (1998).

Total cultivated area in the floodplain is estimated as 230,000 ha (Barbier et al., 1993). Upland or dryland farming is rain-fed, and millet, sorghum and cow-melon are cultivated. *Fadama* farming is mainly rice cultivation. In addition, there are irrigated lands where vegetables may be grown during the dry season. The three main types of irrigation technologies used in this area are identified by Adams (1993) as ditch irrigation, shadoof irrigation and pump irrigation. This study focuses on pump irrigation using water from shallow aquifers. Irrigation farming begins in October, after the floods have receded, and continues up until March/April. The floodplain has experienced a dramatic rise in small-scale irrigation following the introduction of small petrol powered pumps for surface water irrigation and tubewells to tap the shallow aquifers under the floodplain (Kimmage and Adams, 1992; Kaigama and Omeje, 1994). Although the extent of small scale tubewell irrigation within the Hadejia-Jama'are wetlands is not well documented, changes in hydrological conditions, economic conditions, government initiatives, and in particular the policies of World Bank supported Agricultural Development Programs (ADPs) have promoted the use of small irrigation pumps through subsidies and/or loans for tubewell drilling and pump purchase. DIYAM (1987) suggests that shallow aquifers could irrigate 19,000 ha within the wetlands through the use of these small tubewells. NEAZDP (1994) suggests that the annual increase in cropped area within the wetlands is at least 10% and could be higher in areas where water and suitable land is available.

Expansion of dry season cultivation in the area has resulted from the increased availability of small-scale irrigation technology and higher producer prices for some dry-season crops such as peppers, onions and wheat. In the influence area of the Madachi *fadama*, the increase in tubewell irrigation is clearly visible in the large numbers of irrigated fields producing off-season grains such as irrigated rice and wheat and high value perishables such as tomatoes, onions and pepper. The availability of pumps has also resulted in irrigation of certain dry-season crops such as sweet potato, to increase yields, and farmers in the area are experimenting with new commercial crops such as lettuce and garlic. Availability of, and access to, groundwater resources ensures the farmers a more secure and year-round water supply for these crops. Farming in

Table 1
Main commercial crops cultivated

Crop	Percentage of farmers surveyed growing crop (%)
Grains	
Wheat	56.7
Rice	42.4
Vegetables	
Onions	36.4
Spring onions	15.6
Tomatoes	60.6
Pepper (sweet)	27.3
Pepper (chilli)	9.1
Tubers	
Sweet potatoes	12.1

this area is generally subsistence and to hedge against uncertainty farmers practice multi-cropping and inter-cropping. Farmers are, therefore, mainly subsistence oriented agricultural households, also producing cash crops.

3. Economic valuation of dry season irrigated agriculture

Production data on crops grown in the study area are based on the results of field surveys carried out in four villages in the Madachi *fadama* from November 1995–March 1996. The villages of Madachi, Ando, Alaye and Maluri are believed to be representative of the villages in the wetlands, comprising a range of large, medium and small farmers. A total of 37 farms were surveyed for crop production data. In addition, the entire influence area of the Madachi *fadama* was surveyed to establish the number of operational tubewells in the area and a total of 309 operational tubewells were counted during this survey period (HNWCP, 1996). Wheat, tomatoes and pepper are the main cash crops being cultivated in the study area (Table 1). Okra and eggplant (the latter is grown in large quantities where there is surface irrigation) are also grown but mainly for home consumption and in small quantities.

The total area of small scale irrigation using groundwater resources within the Madachi *fadama* and its influence area is estimated to be around 66 km^2, or approximately 6600 ha. [2] The value of the output from the farms surveyed as shown in Table 2. Financial prices for the outputs are estimated from market surveys conducted between December 1995 and May 1996 and from survey findings of farmgate prices received by farmers. Outputs are based on harvest figures reported in sacks or bundles by farmers and converted to weight measures, based on results from the market survey.

The per hectare value for irrigated agriculture in the Madachi area is 36,308 Naira or US$ 412.5 per hectare. The economic value of dry season irrigated agriculture from the Madachi *fadama* influence area (6600 ha) is estimated as 2.39×10^8 Naira or US$ 2,723,077. [3]

4. The production function approach and crop-water relationships

This section develops the underlying general welfare estimation theory based on the production function approach (see Mäler, 1992; Freeman, 1993; Barbier, 1994). The specific production functions for wheat and vegetables based on the production and input data collected by the survey are estimated in Section 5. Based on this analysis and the production functions, welfare estimates related to a change in water input are calculated in Section 6.

4.1. Production function approach

We begin by assuming that farmers produce $I=1, \ldots, n$ crops, irrigated by groundwater. Let y_i be the aggregate output of the ith rop produced by the farmers. The production of y_i requires a water input W_i,

[2] This figure is based on Thompson and Goes (1997) which states that the influence area of the Madachi fadama may be estimated as 136 km^2, assuming a minimum of 1 km radius of influence. The largest extent of the actual swamp area has been estimated as 78 km^2 and we estimate an area of 66 km^2 as being serviced by the recharge from the fadama and as being available for agricultural activities.

[3] Economic prices for the grains are calculated from World Bank data on commodity prices. For non-tradables (i.e. vegetables and tubers), the standard conversion factor is approximately 1 and no additional adjustment is considered necessary since most of the economy uses the black market rate of N88 to US$ 1 for its transactions and faces no foreign exchange premium.

Table 2
Economic valuation of irrigated agriculture for survey villages (area: 20.23 ha)[a]

Crop	Output (kg)	Financial price (per kg)	Economic price (per kg)	Financial benefits (N)	Economic benefits (N)
Wheat	57,250.00	22.00	6.86	1,259,500	392,964
Rice	29,070.00	12.50	12.3	363,375	357,561
Tomatoes	11,030.25	25.60	25.60	282,374	282,374
Onions	21,336.00	4.80	4.80	102,413	102,413
Spring onions	3,280.00	6.25	6.25	20,500	20,500
Sweet pepper	2,607.00	50.10	50.10	130,611	130,611
Chilli pepper	1,423.75	22.00	22.00	31,323	31,323
Sweet potatoes	1,400.00	5.10	5.10	7,140	7,140
Total	127,397.00			2,197,235.40	1,324,886
Financial benefits per ha (N/ha)					108,612.7
Gross Economic benefits per ha (N/ha)					65,491.15
Costs of inputs (N/ha)					29,183.38
Net Economic Benefits per ha (N/ha)					36,307.7

[a] Exchange rate N88=$1.

abstracted through shallow tubewells, and $j=1, \ldots, J$ of other variable inputs (e.g. fertilisers, seed, labour), which we denote as $x_i, \ldots, x_J$ or in vector form as $\boldsymbol{X}_J$. Because of the relationship between recharge and the level of water in the aquifer, we also assume that the amount of water available to the farmer for abstraction is dependent on the groundwater level, R. The aggregate production function for crop i can be expressed as:

$$y_i = y_i(x_{i_1} \ldots x_{i_j}, W_i(R)) \quad \text{for all } i \tag{1}$$

and the associated costs of producing y_i are:

$$C_i = \boldsymbol{C}_x \boldsymbol{X}_J + c_{\mathrm{W}}(R) W_i \quad \text{for all } i \tag{2}$$

where C_i is the minimum costs associated with producing y_i during a single growing season, c_{W} is the cost of pumping water and $\boldsymbol{C}_x$ is a vector of $c_{x_i} \ldots c_{x_J}$ strictly positive, input prices associated with the variable inputs $x_{i_1} \ldots x_{i_J}$. Note that we assume c_{W} is an increasing function of the groundwater level, R, to allow for the possibility of increased pumping costs from greater depths, i.e. $c'_{\mathrm{W}} > 0$, $c''_{\mathrm{W}} > 0$. We first assume that there exists an inverse demand curve for the aggregate crop output, y_i:

$$P_i = P_i(y_i) \quad \text{for all } i \tag{3}$$

where P_i is the market price for y_i, and all other marketed input prices are assumed constant.

Denoting S_i as the social welfare arising from producing y_i, S_i is measured as the area under the demand curve (3), less the cost of the inputs used in production[4]:

$$S_i = S_i(x_{i_1}, \ldots x_{i_J}, W_i(R); c_{\mathrm{w}}(R)) = \int_0^{y_1} P_i(u)\mathrm{d}u - \boldsymbol{C}_x \boldsymbol{X}_J - c_{\mathrm{w}}(R) W_i \quad \text{for all } i, j \tag{4}$$

To maximise (4) we find the optimal values of input x_{i_J} and water input W_i through setting the following first order conditions to zero:

$$\frac{\partial S_i}{\partial x_{i_J}} = P_i(y_i)\frac{\partial y_i}{\partial x_{i_J}} - c_{x_J} = 0 \quad \text{for all } i, j \tag{5}$$

$$\frac{\partial S_i}{\partial W_i} = P_i(y_i)\frac{\partial y_i}{\partial W_i} - c_{\mathrm{w}}(R) = 0 \quad \text{for all } i \tag{6}$$

Eqs. (5) and (6) are the standard optimality conditions indicating that the socially efficient level of input use occurs where the value of the marginal product of each input equals its price. If each farmer is a price-taker, then this welfare optimum is also the competitive equilibrium. We assume that this is the case.

[4] We assume here that the demand function in (3) is compensated, so that consumer welfare can be measured by the appropriate areas. Welfare change is the sum of the consumer and producer surplus measures. However, if the production units are small relative to the market for the final output, and they are essentially price-takers, it can be assumed that product and variable input prices will remain fixed after a change in the environmental resource, W. In this case the benefits of a change in W will accrue to the producers (Freeman, 1993).

The first order conditions in (5) and (6) can be used to define optimal input demand functions for all other inputs as $x_{i_J}{}^* = x_{i_J}{}^*(c_{x_J}, c_{\mathrm{W}}(R), R)$ and for water as $W_i^* = W_i^*(c_{x_J}, c_{\mathrm{W}}(R), R)$. In turn, the optimal production and welfare functions are defined as $y_i^* = y_i^*(x_i^*, \ldots, x_j^*, W_j^*(R))$ and $S_i^* = S_i^*(x_{i_J}^*, \ldots, x_{i_J}^*, W_J^*(R); c_{\mathrm{W}}(R))$.[5]

From the above relationships, we are interested in solving explicitly for the effects on social welfare of a change in groundwater levels, R, due to a fall in recharge rates. Assuming that all other inputs are held constant at their optimal levels, and that all input and output prices (with the exception of c_{w}) are unchanged, it follows from the envelope theorem that:

$$\frac{\mathrm{d}S_i}{\mathrm{d}R} = \left(P_i(y_i^*)\frac{\partial y_i}{\partial W_i} - c_{\mathrm{W}}\right)\left(\frac{\partial W_i}{\partial c_{\mathrm{W}}}\frac{\partial c_{\mathrm{W}}}{\partial R} + \frac{\partial W_i}{\partial R}\right) - W_i^*\left(\frac{\partial c_{\mathrm{W}}}{\partial R}\right) \tag{7}$$

The net welfare change is, therefore, the effect of a change in groundwater levels on the value of the marginal product of water in production, less the per unit cost of a change in water input. The marginal change in pumping costs also affects the total costs of water pumped ($W_i^*(\partial c_{\mathrm{w}}/\partial R)$). The effect of a change in water input due to a change in groundwater levels occurs both directly ($\partial W/\partial R$) and indirectly through the marginal effect of a change in pumping costs on water input (($\partial W_i/\partial c_{\mathrm{w}})(\partial c_{\mathrm{w}}/\partial R$)). As long as per unit pumping costs are not prohibitively high, one would expect an increase in groundwater levels (to a point) to lead to a welfare benefit, or at least to maintain the initial welfare levels, whereas a decrease in groundwater levels would result in a welfare loss, either due to increased pumping costs and/or change in productivity.

If we now assume that all farmers face the same production and cost relationships (1) and (2) for each crop i and are price takers, then it is possible to derive the aggregate welfare effects of a non-marginal change in groundwater levels. Let there be $1, \ldots, k$ farmers producing y_{i_k} output of crop i and using w_{i_k} water inputs. It follows that by integrating (7) over R_0 (old level) to R_1 (new level) and aggregating across all K farmers yields the welfare effects of a no-marginal change in groundwater levels on the aggregate output of crop i.

$$\Delta S_i = \sum_{k=1}^{K}\frac{\Delta S_{ik}}{\mathrm{d}R} = \sum_{k=1}^{k}\int_{R_0}^{R_1}\left[\left(P_i(y_i^*)\frac{\partial y_{i_k}}{\partial W_{i_k}} - c_{\mathrm{W}_k}\right)\times\left(\frac{\partial W_{i_k}}{\partial c_{\mathrm{W}_k}}\frac{\partial c_{\mathrm{W}_k}}{\partial R} + \frac{\partial W_{i_k}}{\partial R}\right) - W_{i_k}^*\left(\frac{\partial c_{\mathrm{W}_k}}{\partial R}\right)\right]\mathrm{d}R \tag{8}$$

Implementing the above welfare measure in (8) requires knowledge of the production function for each crop, as well as how the equilibrium output and inputs change with R. Alternatively, we could measure the aggregate welfare effects directly from changes in social welfare, S_i, in Eq. (4) above. This would imply:

$$\Delta S_i = (S_{\mathrm{R}_1}) - (S_{\mathrm{R}_0}) = \int_0^{y_1} P_i(y_i^*)\mathrm{d}y - \boldsymbol{C}_x\boldsymbol{X}_j^* - c_w(R_1)W_j^*(R_1)\int_0^{y_1} P_i(y_i^*)\mathrm{d}y - \boldsymbol{C}_x\boldsymbol{X}_j^* + c_w(R)W_j^*(R_0) \quad \text{for all } i, j \tag{9}$$

where y_0 is the initial output level and y_1 is the final output level. To use (9) as a welfare measure we would also need to estimate production functions for each crop and calculate optimal levels of inputs and outputs. We return to these welfare measures in Section 6 where, using the information from estimated production functions, we use both measures to calculate welfare change for our sample of wheat and vegetable farmers.

4.2. Irrigation inputs and crop yields

Assessing the importance of groundwater recharge for the maintenance of groundwater at levels suitable for irrigated agriculture requires that we know that (i) the water-yield relationships influencing the crops and (ii) the technological ability of the pumps to pump water. The extent to which crop yields will be affected by changes in water application will depend on a number of factors including, the stage of crop development affected by reduced or no availability of irrigation water; the sensitivity of the crop to fluctuations in water

[5] Asterisks denote optimally chosen quantities.

availability; climatic factors such as evaporation rates; soil factors, including soil type and soil moisture and the length of the growing period. Fig. 1 below depicts seasonal crop response to variable water input showing zones of increasing returns ($0,W$), diminishing returns (W_1,W_2) and negative returns ($>W_2$).

Various functional forms have been used in the literature to describe production technologies using data from field experiments and from observed farm data. The simplest conception of crop response to water application is the linear response and is most likely when the range of application of the variable inputs is small. Log-linear relationships using Cobb–Douglas production functions have also been used to estimate crop-water relationships, although a maximum product is not defined by the Cobb–Douglas and consequently, a decreasing total product (e.g. at high levels of water application) is not possible. A polynomial function such as a quadratic or Gompertz function would allow estimation of the effect of increasing input levels and diminishing marginal returns, as would a Cobb–Douglas translog function, particularly when a wider range of inputs are considered (Hexem and Heady, 1978; Carruthers and Clark, 1981).[6] The survey data used here contains information on actual quantities and market prices of inputs used and yields. It therefore reflects optimisation behaviour on the part of the farmers and is more than a physical relationship between the inputs it reflects economic

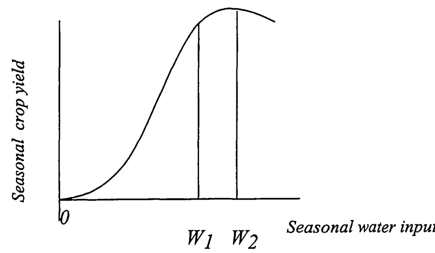

Fig. 1. Crop-water relationships (adapted from Carruthers and Clark, 1981).

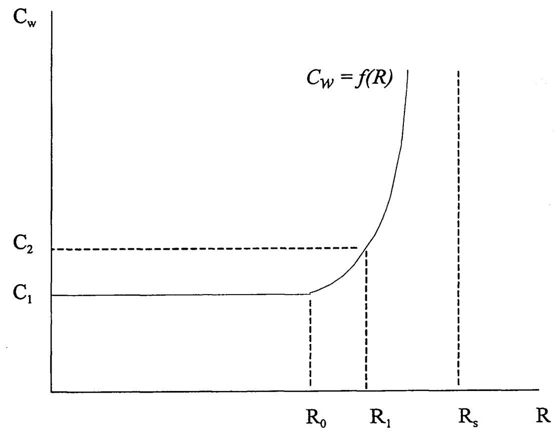

Fig. 2. Water pumping costs as a function of water table depth.

decisions as well. Hence, production functions for the crops are estimated using the survey data.[7]

Before estimating production functions and welfare changes we also consider the technological relationship between groundwater levels and tubewells. A typical tubewell consists of a length of pipe pump casing sunk into the ground below the maximum depth to the water table. This maximum depth should be such that during pumping, the aquifer's water level does not fall below the pipe's reach. If the rate of withdrawal from

[6] Crop-input functions such as Mitscherlich–Spillman functions are often used to estimate effects of changes in water input, given that the application of all other inputs remain constant. These functional forms obey the von Liebig law of the minimum which asserts that there may be non-substitution between some nutrients and a yield plateau. Mitscherlich proposed an exponential functional form specified as:

$$y_i = m(1 - k\mathrm{e}^{-\beta 2_i})$$

where y_i is the observed yield and a_i is the growth factor of the crop. m is defined as the asymptotic yield plateau. The Von Liebig function assumes that output increases linearly in the input up to some maximum. These functional forms have been used with experimental data to study the input-crop production relationship. Experimental data would need to be generated to find the maximum for each input. Yield and output data generated by these agronomic experiments do not, however, reflect optimising behaviour and we use market generated and farm data for the production function estimation.

[7] Cost functions are not estimated, although the literature advocates the estimation of cost function in lieu of production function whenever possible. The cost data in this case is less reliable than the physical data since some or all of the inputs are purchased at subsidy prices, market prices or black market prices.

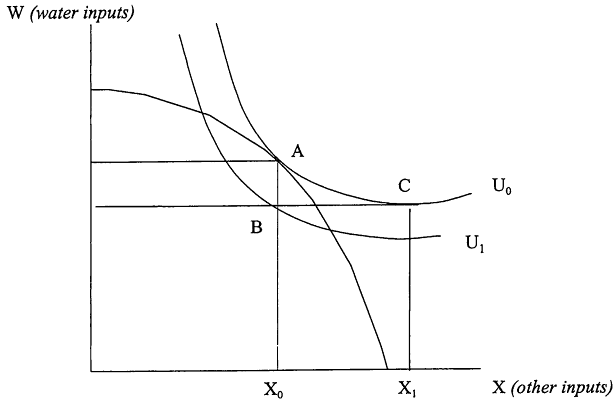

Fig. 3. Effect of a non-marginal change in water table depth on the production possibilities frontier.

the aquifer exceeds the recharge, and groundwater levels do not recover to the original base level, the use of the shallow tubewell will need to be abandoned.[8]

For the purpose of this study, there are two possible effects of a fall in groundwater levels:

(i) as groundwater falls below a certain level, the costs of pumping water are likely to rise, and

(ii) if groundwater levels fall below the maximum depth of the sunken tubewells, the farmer will cease pumping for the rest of the dry season and agricultural production will fall.

Fig. 2 describes the effect of changing groundwater levels on the marginal costs of pumping water and Fig. 3 depicts the effect of changing groundwater levels on the farmer's production possibilities frontier. Water inputs are denoted by W and other inputs by X, while R denotes groundwater levels.

The tubewells in the study area are sunk to depths of approximately 9 m. This implies that the groundwater table would have to fall to a level greater than 9 m (R_S in Fig. 2) before pumping capabilities fall to zero, i.e. for case (ii) to occur. If this occurs, and assuming that all other inputs are held constant, the farmer normally producing at Point A (W_0,X_0) is forced to operate at Point B, defined by (W_1,X_0) in Fig. 3. The farmer's production possibilities frontier (PPF) moves in because of a fall in depth beyond 9 m. He cannot maintain his original level of utility and move to Point C at (W_1,X_1) because this point lies outside the production possibilities frontier (since the farmer cannot change input decisions during the season). The farmer will, therefore, operate at Point B and produce a lower output, or not produce at all.[9] At R_S, the discontinuity that sets in due to technological limitations, in effect drives the cost of pumping water to infinity for the farmer. This non-convexity in the cost curve may be offset by technological innovation. However, given the present level of technology, if the water levels stay below 9 m, the farmer will not be able to irrigate at all and the associated drop in yield can be calculated from the production function by setting water input to zero. This is only expected to occur in the wetlands if there is a long period of very low flooding and no technological change.

For case (i) to occur, we expect that the speed of the pump will be affected by a drop in groundwater levels but water will still be available to the farmer using the given technology. The pumps being used in the floodplain are surface mounted pumps, and it is likely that at depths approaching 7 m (denoted as R_1 in Fig. 2),

[8] However, increased costs of pumping from a greater depth may cause pumping to be curtailed until a new groundwater level is established. Because the farmer is forced to stop pumping, water levels may recover, allowing some sporadic pumping throughout the season. This introduces uncertainty into the problem and makes it a dynamic problem. This is beyond the scope of the present paper.

[9] We are assuming no technology shifts in this case since, in the short run, the farmer is unable to change technologies. There are high financial costs associated with the change in technology to deeper boreholes and very few farmers were observed to be using the deep boreholes for irrigation. The small pumps are subsidised and are being promoted by government and bilateral organisations.

these pumps will slow down because of the increase in lift. To maintain input levels, the farmer would have to increase pumping hours, thereby incurring higher costs of production (C_1). However, the farmer may be able to continue production in the short run. Using the data on pumping hours and the specifications of the pumps being used, we estimate that as water levels drop from 6 m to 7 m, pump speeds will decrease from 37,636 l/h to 26,434 l/h (approximately 30% decrease in speed). [10]

We use this information to calculate the unit pumping cost at the new groundwater level, R_2. As Fig. 2 shows, $C_w(R)=C_0$ for levels of $R \leq R_0$. Pumping costs increase thereafter. By linearising the cost function between R_0 and R_1 in Fig. 3, we derive the functional relationship between pumping costs, c_w and groundwater level R for $R_0 \leq R \leq R_1$ as:

$$c_W(R) = a + bR \tag{10}$$

where $a=-19.56$; $b=5.34$.

Note that this functional form, with the values for a and b as noted above, only describes the portion of the curve between R_0 and R_1 in Fig. 2. We can estimate the change in pumping costs due to a fall in groundwater levels using the above relationship and the welfare measure in (9). Increases in pumping costs will also affect the level of water input during the growing season and optimal levels of water input and associated change in output levels can be calculated from the production functions, estimated in Section 5, and the optimality conditions in (5) and (6).

5. Estimating production functions for wheat and vegetables

In the production functions estimated below, we assume that output (y) depends on land (L), labour (B), Seeds (S), fertiliser (F) and water inputs (W). The farmers in the Madachi area mainly grow wheat, irrigated rice and vegetables. The crops are divided into these three groups because of the different nature of irrigation, fertiliser application and other farming decisions. Wheat and rice are generally grown earlier in the season and vegetables are grown well into the dry season. In the following sections, we estimate production relationships for wheat and vegetables only since irrigated rice is grown by very few farmers in the sample. [11]

We consider linear and log-linear functional forms for wheat and vegetable production. [12] The linear form assumes constant marginal products and excludes any interaction between the inputs. Although the lack of interaction terms is restrictive, we observe in the literature that linear relationships are likely, particularly for wheat production and with low levels of inputs. The log-linear form assumes constant input elasticities and variable marginal products. Note that the coefficients estimated by using this form represent output elasticities of individual variables and the sum of these elasticities indicates the nature of returns to scale. Table 3 lists the variables used in the analysis. The estimated linear and log-linear production functions for wheat are:

$$Y = \alpha + \beta_1 L + \beta_2 B + \beta_3 S + \beta_4 F + \beta_5 W + \varepsilon_1 \tag{11}$$

$$\ln Y = \alpha + \beta_1 \ln L + \beta_2 B + \beta_3 \ln S + \beta_4 \ln F + \beta_5 \ln W + \varepsilon_2 \tag{12}$$

and ε_i is the random disturbance associated with the production function.

The production function for vegetables was also estimated as a single function since all the vegetables

[10] Although, theoretically per unit costs of pumping water should be constant for the given technology, surface mounted pumps are less efficient at groundwater depths approaching 7 m. If costs are constant the welfare change for the farmer would be measured by:

$$\frac{\mathrm{d}S_i}{\mathrm{d}R} = \int_{R_0}^{R_1} \left[\left(P_i(y_i^*) \frac{\partial y_i}{\partial W_i} - c_\mathrm{w} \right) \left(\frac{\partial W_i}{\partial R} \right) \right] \mathrm{d}R$$

[11] Since crop level data is often not available, many studies analyse farm level aggregated input demands. Although fixed factors, such as land, may cause jointness in the production process, we argue that crop level production functions can be estimated in this case for wheat and for vegetables since (1) crop level data was collected through the survey and is available and (2) vegetables are clearly grown only after the winter wheat production implying that input decisions may be considered as separate in terms of the production processes.

[12] Although a quadratic function allowing interactions between variables was also fitted to the data, the results are not reported here. The small sample size for wheat production (21 farmers) makes it impossible to include all the variables specified by the quadratic model in the estimation. The model requires 18 degrees of freedom to estimate. The quadratic function for vegetables also performs poorly.

Table 3
Table of variable names

Variable	Definition
Y	Output (kg)
L	Land (ha)
B	Labour (workers)
F	Fertiliser (kg)
S	Seeds (kg)
W	Water (l)
LY	LN (Y)
LL	LN (Land)
LB	LN(Labour)
LF	LN (Fertiliser)
LS	LN(Seeds)
LW	LN(Water)

are grown at the same time (after the wheat has been harvested) or in quick succession and receive similar quantities of inputs. Data on seeds/seedlings (S) was unreliable and this variable was dropped from the above estimated production functions (11) and (12) for vegetables.

Table 4 reports the results for the linear and log-linear functions for wheat production. The linear model has an R^2 of 0.93 and F statistic of 54.4. Both the values suggest a good fit. The Breusch–Pagan Lagrange Multiplier test is not significant for the linear model (critical value for LM χ^2=13.27; with 5 d.f.), and we accept the hypothesis of homoscedasticity. However, the large, negatively signed and statistically significant value for the constant term would suggest that there might be misspecification of the functional form.

The log-linear functional form also performs well in terms of R^2 (0.9) and F statistics (37.49). The coefficients for LW and LF are found to be statistically significant in the log-linear model, with the expected signs. The Lagrange multiplier statistic is however significant for the log-linear model, indicating some heteroscedasticity in this model. The presence of this heteroscedasticity indicates that the least squares estimators are still unbiased but inefficient. Since the estimators of the variances are also biased we correct for the standard errors of the coefficients and find relatively small differences in the values. The log-linear model is, therefore, considered as the most satisfactory version of the wheat production function. According to the literature on crop-water production functions determined from experimental studies, wheat is often seen to have a linear or log-linear shape unlike other crops which may show diminishing returns at high levels of water application. Wheat may continue to show increasing returns up to fairly high levels of water application (Hexem and Heady, 1978; Carruthers and Clark, 1981).

Table 5 reports the econometric results for the functions estimation for vegetable production. The linear

Table 4
Results for the wheat production function[a]

Variable	Linear	Log-linear
Land	1993.7[b] (2.865)	–
Labour (B)	52.711 (0.824)	–
Seeds	3.6165[c] (2.566)	–
Fertiliser	71.581[c] (2.438)	–
Water	11.610[c] (2.134)	–
LL	–	0.38 (1.442)
LB	–	−0.024 (0.156)
LS	–	0.026 (0.33)
LF	–	0.47[b] (2.71)
LW	–	0.6885[d] (1.881)
Constant	−1662.5[b] (3.598)	3.4[c] (2.39)
Adjusted R^2	0.93	0.9
F statistic	54.4	37.49
Breusch–Pagan χ^2	1.05 (d.f.5)	18.27 (d.f.5)
Observations	21	21

[a] t statistics in parenthesis.
[b] 2% significance level.
[c] 5% significance level.
[d] 10% significance level.

Table 5
Results for the vegetable production function[a]

Variable	Linear	Log-linear
Land	−786.67 (−0.524)	–
Labour (B)	282.76[d] (1.591)	–
Fertiliser	265.04[c] (2.380)	–
Water	5.8358[c] (2.433)	–
LL	–	0.231 (0.823)
LB	–	0.585[c] (2.206)
LF	–	0.593[b] (2.827)
LW	–	0.4268[c] (2.437)
Constant	−1449.4 (1.512)	3.13[b] (11.439)
Adjusted R^2	0.55	0.66
F statistic	11.9	18.88
Breusch–Pagan χ^2	13.49 (d.f.4)	4.24 (d.f.4)
Observations	37	37

[a] t statistics in parenthesis.
[b] 1% significance level.
[c] 5% significance level.
[d] 10% significance level.

and log-linear models again perform well in terms of R^2 and F statistics. The Breusch–Pagan Lagrange Multiplier test is significant for the linear model (χ^2=13.49; with 4 d.f.), and we reject the hypothesis of homoscedasticity. For the log-linear model, the Lagrange multiplier statistic is less than the critical value at the 5% significance level (χ^2=4.24; with 4 d.f.), indicating no heteroscedasticity in this model. The coefficients on the variables LF, LB, LW and the constant term are statistically significant.

6. Valuing the recharge function

Hydrological evidence for the relationship between flood extent and recharge to village wells show that there is some fluctuation with flood extent and mean water depth of the shallow aquifer. The effect of planned upstream water projects will have an impact on producer welfare within the wetlands through changes in flood extent therefore groundwater recharge. By hypothesising a drop in groundwater levels from 6 m to 7 m in depth (due to reduced recharge in the current period), we calculate the expected change in welfare associated with this reduction in recharge. This exogenous change affects the farmers decision making process during the farming season, i.e. after decisions on other inputs have already been taken since the effect of the reduced recharge will not be felt until after the dry season agriculture has started.

Recall that in Section 4.1, the welfare change measure for non-marginal changes in R (level of naturally recharged groundwater) is given by (8). This welfare change measure is used together with the results of the production function estimates to calculate welfare changes for individual farmers. We also assume that farmers in the Madachi area are price takers and hence face a 'horizontal' demand function, i.e. $P_i(y_i)=P_i$.

From Eq. (8) we see that the effect of R on welfare is felt through a change in water input due to increased costs ($(\partial W_i/\partial c_{\mathrm{W}})$) and/or a change in water availability ($\partial W_i/\partial R$). This second effect will occur only if a change in recharge were to cause a decline in groundwater levels below 9 m (see Section 4.2 and Fig. 3 above). This is unlikely to happen within a single season and we do not therefore consider this aspect in calculating welfare change. Instead we consider the effect of changing pumping costs on water input and use the production function estimated earlier for the purpose of estimating welfare changes. However, in order to do so, we need to calculate ($\partial W_i/\partial c_{\mathrm{W}}$), the marginal change in water demand due to a marginal change in the cost of pumping.

In Section 5 we estimated production functions for wheat and vegetable production. Holding all other inputs constant and noting that only water input will vary, we use the log linear production functions estimated in Section 5, together with the optimality conditions in Eqs. (5) and (6) to solve for W_i as:

$$P_i\alpha\beta_{\mathrm{W}}L^{\beta_{\mathrm{L}}}B^{\beta_{\mathrm{B}}}S^{\beta_{\mathrm{S}}}F^{\beta_{\mathrm{F}}}W^{\beta_{\mathrm{W}}-1}=c_{\mathrm{W}} \tag{13}$$

$$W_i^*=\left(\frac{c_{\mathrm{W}}}{P_i\alpha\beta_{\mathrm{W}_j}L^{\beta_{\mathrm{L}}}B^{\beta_{\mathrm{B}}}S^{\beta_{\mathrm{S}}}F^{\beta_{\mathrm{F}}}}\right)^{1/(\beta_{\mathrm{W}_i}-1)} \tag{14}$$

where L,B, S and F are all the other inputs in the specified production function (for crop i) with estimated parameters β_{L}, β_{B}, β_{S} and β_{F}.[13] We solve for($\partial W_i/\partial c_{\mathrm{W}}$) as:

$$\frac{\partial W_i}{\partial c_{\mathrm{W}}}=\frac{1}{\beta_{\mathrm{W}}-1}\left(\frac{c_{\mathrm{W}}}{P\alpha\beta_{\mathrm{W}}L^{\beta_{\mathrm{L}}}B^{\beta_{\mathrm{B}}}S^{\beta_{\mathrm{S}}}F^{\beta_{\mathrm{F}}}}\right)^{(2-\beta_{\mathrm{W}})/(\beta_{\mathrm{W}}-1)}\times\left(\frac{1}{P\alpha\beta_{\mathrm{W}}L^{\beta_{\mathrm{L}}}B^{\beta_{\mathrm{B}}}S^{\beta_{\mathrm{S}}}F^{\beta_{\mathrm{F}}}}\right) \tag{15}$$

This is calculated for each farmer, using the estimated values for the relevant parameters and constant terms and the market price of the crop.

We now calculate welfare change due to a drop in groundwater levels to 7 m, for individual farmers, using the welfare measures in Eq. (8) or Eq. (9) (see Appendix A for the derivation of expressions used to calculate welfare changes). The production functions from Section 5 are used to calculate the associated change in productivity due to a fall in recharge levels. We calculate optimal levels of water input from (13) and output levels from the production function. The average and total change in welfare for a drop in groundwater levels from 6 to 7 m depth, using both welfare measures (8) and (9), are given below. From (8), the welfare change of a drop in groundwater levels (R) to 7 m is calculated as given in Table 6. From

[13] Note that for the vegetable production function, the variable S (seeds/seedlings) is not included and is therefore not included in the estimation of W_i either.

Table 6
Welfare change for sample using Eq. (8)

Crop	Total welfare change (Naira)	Average welfare change per hectare	Total land (ha)	Average land holding (ha)
Wheat	551,201	54,459	10.51	0.645
Vegetables	105,916	3,566	29.7	0.803

Table 7
Welfare changes for sample using Eq. (9)

Crop	Total welfare change (Naira)	Average welfare change per hectare	Total land (ha)	Average land holding (ha)
Wheat	550,320	54,372	10.51	0.645
Vegetables	130,659	4,399	29.7	0.803

(9), the welfare change of a drop in groundwater levels (R) to 7 m is calculated as in Table 7.

As expected, there is only a small variation between the results from using the two welfare change measures. The welfare change associated with the effects of groundwater loss on wheat production is very high. Although vegetable production is, in general, more water intensive, it appears that wheat production is more sensitive to changes in water input. The elasticity of production to water inputs for wheat is higher than it is in the case of vegetable production. However, vegetable production takes place well into the dry season and may be subject to even higher pumping costs for water if the water table falls below 7 m during the dry season. To properly measure this welfare change we would, however, require knowledge of the full relationship between pumping costs and groundwater levels. Since there is little evidence that groundwater levels could fall much below 7 m we have restricted our present analysis to this level for both wheat and vegetable production.

The Madachi *fadama* affects an area of about 6600 ha. Although there are at least 963 tubewells installed in the area, only 309 were found to be currently operational (i.e. 32% of installed tubewells are operational). Approximately 56.7% of the farmers in this area grow wheat while 100% of the farmers grow vegetables. This implies that 56.7% of the farmers would be affected by the welfare change associated with growing wheat and vegetables and 43.3% would be affected by the welfare change associated with growing vegetables only. We assume there are a corresponding number of farmers for each of the 309 operational tubewells and conclude that there are 175 wheat and vegetable farmers and 134 vegetable farmers in the Madachi fadama influence area. We use the welfare change measures for a fall in groundwater levels from 6 to 7 m depth from Eq. (9) for the welfare changes reported in Table 8.

This study shows that irrigated agriculture using water from the shallow groundwater aquifer has a value of 36,308 Naira (US$ 413) per hectares for the Madachi area. The change in welfare associated with a decrease in recharge to the aquifer is estimated as 2,863 Naira (US$ 32.5) for each vegetable farmer and as 29,110 Naira (US$ 331) for farmers growing wheat and vegetables. Average household income is the study area is Naira 3,155 per month (Acharya, 1998) and welfare loss estimated by this study, therefore, amounts to approximately 7.56% of yearly income for veg-

Table 8
Welfare change in the Madachi fadama in Naira[a]

	Average welfare change per farmer	Total loss for Madachi farmers
Vegetable farmer	2,863	383,642
Wheat+vegetable farmer	29,110	5,094,296

[a] Exchange rate: 88 N=US$ 1.

etable farmers and 77% of yearly income for vegetable and wheat farmers. The total loss associated with the 1 m change in naturally recharged groundwater levels (resulting in a decline of groundwater levels to approximately 7 m) is estimated as 5,477,938 Naira (US$ 62,249) for the influence area of the Madachi *fadama*.

The welfare estimates for wheat are surprisingly high. It is argued that the reason for this is that wheat is a newly introduced crop within the wetlands and because of its recent introduction displays a high yield response to water inputs. Since our data is collected over a single dry season, this is reflected in our results. Continued production of wheat within the wetlands could be subject to declining yields over time and is generally considered to be unsustainable within the wetlands over the long run (Barbier et al., 1994). Disregarding wheat production the estimated welfare loss is therefore 383,642 Naira or US$ 4360 for the study area.

DIYAM (1987) suggested that shallow aquifers could irrigate 19,000 ha within the wetlands through the use of small tubewells. Using the average welfare change for the study area of 5478 Naira/ha or US$ 62/ha, we estimate a welfare loss of 1.04×10^8 Naira or US$ 1,182,737 for the wetlands, due to a decrease in groundwater levels to approximately 7 m in depth. [14] Again disregarding wheat production, the welfare loss associated with this change in groundwater levels, amounts to 82,832 US$ for the wetlands. Although there is considerable difference in the level of welfare loss with and without consideration of wheat production, the value of groundwater recharge in terms of irrigated agriculture is clearly positive and significantly large.

7. Conclusions and policy implications

The emphasis on increasing tubewell irrigation within the wetlands is contradictory to policies such as dam construction and channelization that would reduce flooding within the wetlands. The economic value of the opportunity costs associated with diverting this water away from the wetlands has not been fully realised and incorporated into the development plans for this region. Although there is at present apparently little concern for the over-exploitation of groundwater resources, this optimism is based on relatively little data on aquifer recharge and the effect of increased or reduced flooding of *fadama* areas. Cropping patterns in the area have changed due to credit and technological facilities as well as due to changing hydrological conditions. Increasing dependence on small-scale irrigation for dry season crops may also result in increased sensitivity of small farmers to changes in prices and market demand. As previous studies have asserted, and as this study confirms, groundwater recharge is of considerable importance to wetland agriculture and reduced recharge resulting in lower levels of groundwater will result in high welfare losses for the floodplain populations. Furthermore, this analysis has been conducted in the Madachi *fadama*, a regularly inundated area with good groundwater stocks. It is very likely that in other areas of the wetlands where flooding is not as reliable as in Madachi, the effects of reduced recharge and rapid declines in groundwater levels will have more devastating effects.

It is also conceivable that given a dramatic fall in groundwater recharge, there may be a technological shift towards deeper tubewells and boreholes for irrigation. Many boreholes in the wetlands are sunk over 100 m deep. In contrast, most of the village wells and shallow tubewells are less than 10 m deep. The boreholes may, therefore, be sunk in deeper aquifers. The exact relationship between the alluvial aquifers and the deeper aquifers of the Chad Formation is not known and needs to be further investigated. In places there may be some connection between the two so that flooding within the wetlands may recharge the deeper aquifers as well. The move towards deeper boreholes in some parts of the wetlands appears to be both economically and politically motivated. Irrigation boreholes (sunk to levels greater than 10 m depth) will transform the agriculture in the area and may offset any impact of falling groundwater levels in the shallow aquifer. However, given the lack of hydrological information regarding the hydrological pathways between the deeper aquifer and the shallow aquifer, the question of groundwater mining and hence, potentially

[14] Note that this figure is based on the percentage of installed tubewells actually working during the study period (32%) and could be much higher for a higher percentage of operational tubewells within the wetlands.

unsustainable developments within the wetlands, cannot be ruled out. In the face of this uncertainty, the value of the shallow aquifers in irrigated agriculture, and consequently the value of the recharge function of the wetlands, must be recognised by policies affecting hydrological conditions within the floodplain.

Appendix

Specifically, for each farmer the expression used in calculating welfare change from (9) is:

$$(S_{\mathrm{R}_1}) - (S_{\mathrm{R}_0}) = (P_i\, y^1 - \boldsymbol{C}_x \boldsymbol{X}_j^* - c_{\mathrm{W}}(R_1) W_i^*(R_1)) \\ -(P_i\, y^0 + \boldsymbol{C}_x \boldsymbol{X}_j^* + c_{\mathrm{W}}(R_0) W_i^*(R_0))$$

We use optimal values for water input levels, evaluated at the different unit costs of pumping c_1 and c_0, assuming all other inputs remain constant. Optimal levels of output, y^1 and y^0, are then calculated for each farmer at the estimated optimal water input levels. Similarly, we integrate Eq. (8) over R, deriving the following expression:

$$\frac{\mathrm{d}S}{\mathrm{d}R} = \left[\frac{\{(1/2)\beta_W \phi^\gamma R^2 a - \beta_W b \phi^\gamma R \\ -((aR-b)^{\gamma+1}/a(\gamma+1))\}\gamma a}{\phi^\gamma} - \frac{\{(aR/\phi) - (b/\phi)\}^{(\gamma+1)}}{\gamma+1}\phi \right]_{R_0=6}^{R_1=7}$$

Evaluating for R=[6,7], we derive the following expression:

$$\frac{\mathrm{d}S}{\mathrm{d}R} = \frac{1}{2} \frac{\{49\beta_{\mathrm{W}}\varphi^{\mathrm{Y}} a^2\gamma^2 + 49\beta_{\mathrm{W}}\varphi^\gamma a^2 \gamma \\ -14\beta_{\mathrm{W}} b\phi^{\mathrm{Y}} a\gamma^2 - 14\beta_{\mathrm{W}} b\varphi^{\mathrm{Y}} aYY^2 \\ ((7a-b)/\varphi)^{y+1}\varphi\varphi^{Y} - 2Y(7a-b)^{y+1}\}}{(YY^1)\varphi^{\mathrm{Y}}}$$

$$-\frac{\{18\beta_{\mathrm{W}}\varphi^{\mathrm{Y}} a^2 Y^2 + 18\beta_{\mathrm{W}}\varphi^{\mathrm{Y}} a^2 y \\ -6\beta_{\mathrm{W}} b\varphi^{\mathrm{Y}} aY^2 - 6\beta_{\mathrm{W}} b\varphi^{\mathrm{Y}} aYY^2 \\ ((6a-b)/\varphi)^{y+1}\varphi\varphi^{\mathrm{Y}} - Y(6a-b)^{(\mathrm{YY1})}\}}{(YY^1)\varphi^{\mathrm{Y}}}$$

where a and b are as defined in (12); $= (1/\beta_{\mathrm{W}}) - 1$; $= \quad P_i \alpha \beta_{\mathrm{W}_i} L^{\beta_{\mathrm{L}}} B^{\beta_{\mathrm{B}}} S^{\beta_{\mathrm{S}}} F^{\beta_{\mathrm{F}}}$

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