THE ECONOMICS OF WATER LIFTING FOR SMALL SCALE IRRIGATION IN THE THIRD WORLD: TRADITIONAL AND PHOTOVOLTAIC TECHNOLOGIES

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ABSTRACT

Much of the non-traditional, irrigated, agricultural land in developing nations utilizes pumping technologies which have been adapted from the developed nations. These technologies are adaptable to the medium and large scale farms (individual farms in excess of 2 hectares) but are not adaptable to smaller farms. It has been these larger third world farmers who have been able to take the fullest advantage of the benefits of new seed varieties in wheat and rice combined with fertilizer and water, the ingredients of the "green revolution." This short paper summarizes the experience to date of developing water pumping systems for small farms in selected deltaic areas of the 'third world,' those areas in which irrigation water is available at depths between 1.5 and 4.5 meters (m). These areas include the Nile, Euphrates, Indus, Ganges, Irrawaddy, and Mekong River Basins which combined encompass 50 million hectares of the earth's surface (less than one percent of the earth's land area) and contain roughly 250 million people (nearly 7 percent of the world's population).

The analyses evaluate water supplied by traditional means--human and animal--by conventional systems--diesel, gasoline and electric--and by renewable resource systems, in particular photovoltaic powered systems. A review of previous studies indicate that the value of water for irrigation is in the range of two to three cents (U.S.) per cubic meter (m^3). The methods of lifting water, available to farmers on land areas of one hectare or less, provide water at costs in excess of this two to three cents (U.S.) per m^3. Investigations of the Shadoof systems of North Africa and Asia show costs of water as high as seven cents (U.S.) per cubic meter. An evaluation of animal power used to operate a Persian wheel resulted with water costs that varied with the amount of feed required by the animal from 1 to 4¢/m^3.

Four pumping systems were investigated using conventional power systems: two diesel, one gasoline, and one electric. Since pumping systems have relatively fixed sizes and prices, the costs generally exceed the benefits for the small farmer. The cost per cubic meter for irrigating one hectare averaged: 3.5¢ (U.S.) for diesel in Chad; 4.0¢ (U.S.) for gasoline in Chad; 3.5¢ (U.S.) for diesel in India; and 3.0¢ (U.S.) for electricity in India. In each of these instances, the cost of supplying small scale farmers with water using conventional systems was greater than the economic value of the water supplied. A fifth pumping system investigated herein utilized a high technology power system, photovoltaic cells combined with efficient electric motor and pump devices. The cost of providing water utilizing the photovoltaic power system resulted in costs of 2.8¢/m^3 (U.S.) to lift the water 1.5m and 5.4¢/m^3 (U.S.) for lifting heads of 4.5m, at today's cell prices ($10/Wp). If photovoltaic power system costs are reduced to $4.00 per peak watt (Wp), the cost of irrigation water for a lift of 1.5m would be 1.2¢/m^3, and for a lift of 4.5m would be 2.3¢/m^3.

TABLE OF CONTENTS

LIST OF TABLES AND FIGURES

IRRIGATION IN THE DEVELOPING NATIONS

The economic development of rural communities in most developing nations is heavily dependent upon increased agricultural productivity. For rural populations, particularly on the margin, to survive and indeed to raise their economic position, requires increased return from small as well as from large land holdings. This paper focuses attention on the economics of irrigation of small farms (0.5 to 2 hectares) in developing countries. In so doing, the experience of the "green revolution" reaching small farmers, the economics of both traditional and conventional pumping systems for small farms, and finally, the competitive advantage of microscale photovoltaic (solar cell) powered irrigation systems is analyzed.

The development of new varieties of wheat and rice was hailed as the turning point in agricultural development and the farmers' income distribution for the developing nations. While the benefits of the "green revolution" have been enjoyed by medium- and large-scale farmers, the small, frequently marginal farmer has been unable to take advantage of the benefits of new varieties of crops, largely because irrigation water has been either unavailable or too expensive.

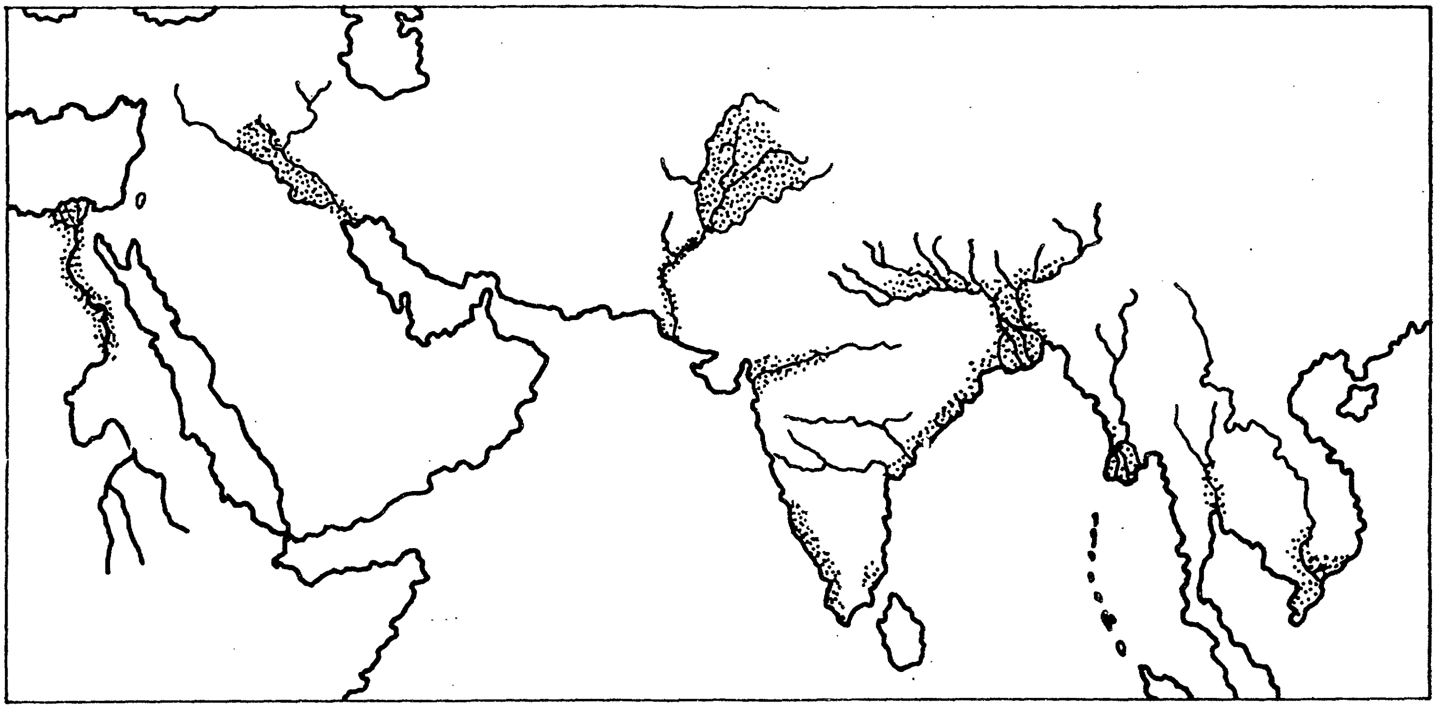
Evidence of the constraint to increased crop production (and potential income) caused by lack of water has been exhibited by virtually all regions which have a predominance of small farm holdings. Thus, while the wheat growing Punjab of Pakistan and India benefited dramatically[1] from the "green revolution," the small farm, predominantly rice growing, deltaic areas such as the Ganges (Bangladesh) or Mekong (Vietnam) have not experienced the same level of benefit from improved crop varieties. Nonavailability of reliable water supply in dry seasons which allows for multiple cropping of land has played a major role in differentiating between benefits to large and small farmers.

Both Bangladesh (formerly East Pakistan) and Vietnam have been the site of detailed analyses of the benefits of irrigation. J. W. Thomas and others, in their analysis of the Rural Works program of East Pakistan, described pumping as the principal means of providing water to small farmers in the delta area.[2] Thomas studied communal/cooperative water pumping groups within rural communities where he found that the pumps themselves tended to be monopolized by the relatively larger of the small farmers and the actual number of hectares irrigated decreased as the number of farmers within a pump group increased. Evidence from Vietnam, as reported in the work by Sansom in <u>Economics of Insurgency in the Mekong Delta of Vietnam</u> again indicates that smaller farms, whose mean area is 1.2 hectares, are incapable of taking advantage of the motor pump technology unlike large farmers (mean 2.5 hectares).[3] There has been considerable recent work, unpublished to date, which attempts to estimate the value of irrigation water in a range of environments. As will be discussed later, Smith and Allison have used a value, for water to small farms in deltaic areas, equivalent to an increase in yield of 2.5 metric tons per irrigated hectare.[4] The work of a number of researchers at the International Food Policy Research Institute has indicated benefit values in the range of 1.4 tons per hectare.[5] Econometric analysis by Alan Strout of MIT has shown values of from 1.4 to 3.0 metric tons per hectare.[6] Sansom in his work on Vietnam has shown output to double with the introduction of the motor pump. In general all of these values roughly translate into a value for irrigation water in the range of 2¢ to 3¢ (U.S.) per m^3 of water pumped.[7]

The work of Sansom on farming in the Mekong Delta is significant in this analysis for two reasons. The first is that the motor pump technology employed for water lifting was indigenously developed; it was an inexpensive low technology development and was readily available in the local market, yet still was not economic for the smallest of landholders. The second point of importance is that the motor pump entered the economy of rural Vietnam at an unprecedented rate. Sansom reports of districts whose farm adoption of motor pumps increased from zero to 50% in less than four years.[8] Therefore the provision of irrigation water is expected to bring a rapid economic benefit, quickly recognized by the traditional farmer.

The information concerning water pumping in the Punjab, Bangladesh and the Mekong points to two significant conclusions. First, provision of reliable supplies of water brings economic benefit, and second, these benefits do not accrue to farmers below a specific threshold. The remainder of this paper focuses attention on provision of water to small farms (0.5 to 2 hectares), specifically in water lifting environments which require minimal amounts of energy, i.e., those areas requiring water lifts in the range of 1.5 to 4.5 meters. Figure 1 shows graphically the areas of the world in which this water regime exists, primarily the large alluvial deltas of Asia, North Africa and Arabia. These regions account for 50 million hectares of land and a population of over 250 million.

Figure 1 DELTAIC SMALL FARM REGIONS OF THE MIDDLE EAST, SOUTH AND SOUTHEAST ASIA



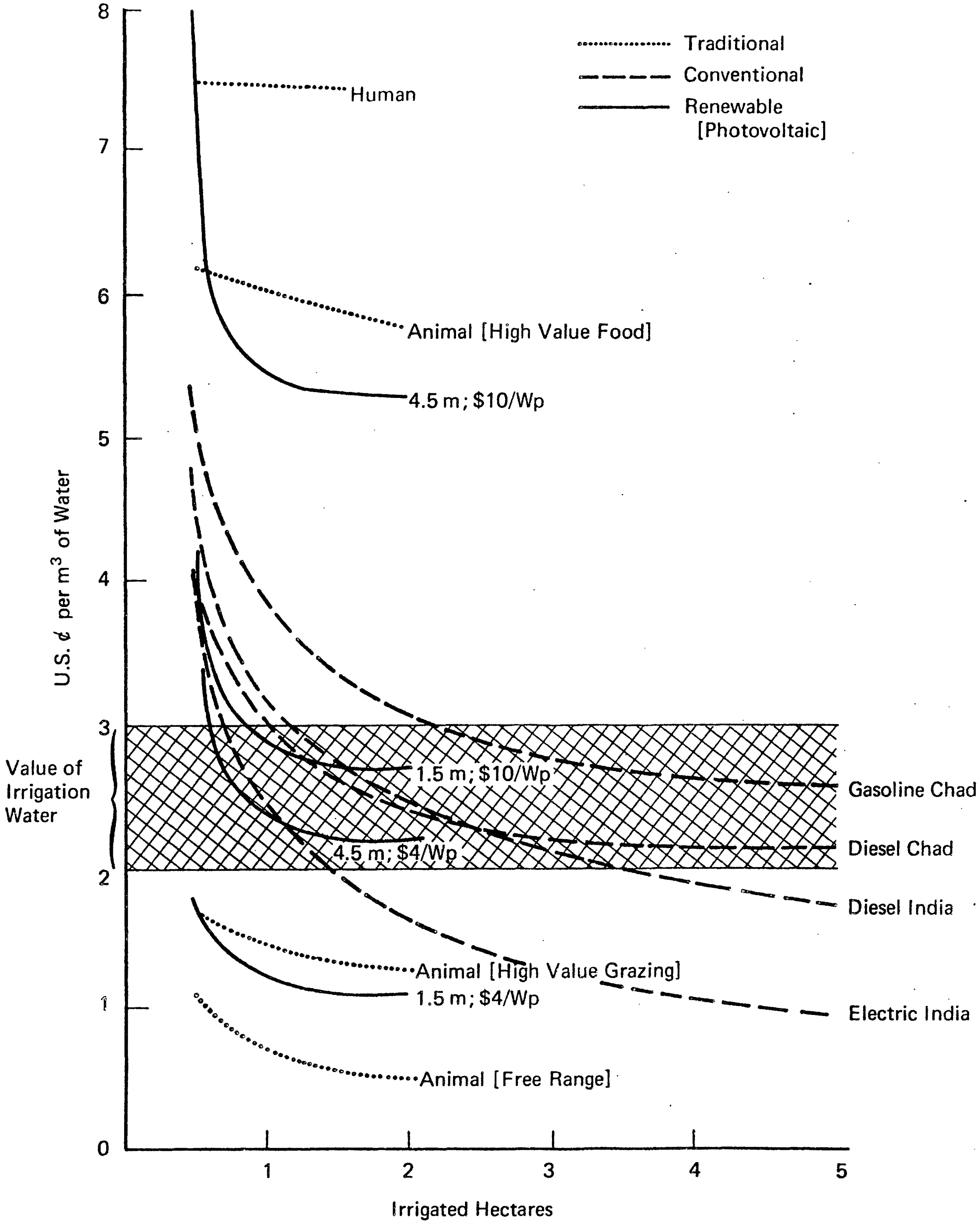
Country	Rivers	Alluvial Valleys and Deltas Population (million)	Area (million hectares)
Egypt	Nile	25	2.5
Iraq	Tigris, Euphrates	7	4.0
Pakistan	Indus	20	6.0
India	Ganges, and	130	23.0
Bangladesh	Brahmaputra	45	8.0
Burma	Irrawaddy	3	2.0
Thailand	Chao Phrya	2	0.5
Vietnam	Mekong	18	5.0
		250	50.0

ECONOMICS OF TRADITIONAL/CONVENTIONAL IRRIGATION METHODS

Traditional methods of water lifting over relatively low heads have utilized both human and animal power.[9] Figure 2, which summarizes the economics of all water lifting systems discussed herein, shows the cost of water lifting using human power with a relatively efficient system, the Shadoof, employed in much of Africa and Asia. While detailed economic analyses were not carried out for a range of human powered irrigation systems, man in general is not an economic machine in such tasks as water lifting, where his food requirements nearly equal the incremental production from the water pumped. The Shadoof has been used as an example of a relatively efficient system still costing roughly 7.5¢/m^3 of water.

Irrigation water from animal power is available over a range of costs primarily as a function of the cost of food for the animal. As shown in Figure 2, these values vary widely. Numerical values presented are for a camel operating a Persian Wheel in Chad. The results are, within the errors of estimation, similar to those available for other animals such as bullocks operating similar Persian Wheel lifts in south and southeast Asia. In general, if it is necesary to feed the animal from forage crops grown on the irrigated land, the cost of irrigation water is betwen 5.5¢/m^3 and 6.5¢/m^3 (U.S.). If animals can be fed on crops grown or harvested from non-irrigated lands the cost may be reduced dramatically to from 1.5 to 1.7¢/m^3, and further reduced to from 0.6 to 1¢/m^3 when animals can be left to forage for themselves. For the majority of the deltaic areas under analysis in this study, availability of land for forage is limited, particularly for the small farmer. As

Figure 2 VALUE AND COST OF IRRIGATION WATER



farm size decreases, the cost of maintaining (feeding) work animals increases, effectively removing draft animals from consideration on farms of one hectare or less.

Conventional small on-site irrigation pumping schemes range in size from roughly 0.5 cubic feet per second (cusec) to 2 cusec systems. For the deltaic areas, such pumping systems are either pumped wells (tube wells) or low lift systems. Figure 2 summarizes water costs for four pumping systems, two in Chad and two in India.[10] The pumping systems analyzed for Chad represent conventional gasoline and diesel systems utilizing 0.5 cusec pumps with available power packs of 7.5hp. Gasoline powered pumping systems of this magnitude are presently available. However, the diesel system was assembled on paper for the purposes of this analysis. As can be seen, the fixed capital portion of the investment in conventional pumping systems makes them only marginally economic at farm sizes of 2 hectares and uneconomical on farms below 1 to 1.5 hectares in area.

Two points should be made concerning the conventional pumping systems for Chad included in Figure 2. First, both the gasoline and the diesel systems are not specifically designed for low water head operation and as a result are overpowered for the required task. However, these systems employ pump and motor combinations generally used in both the United States Agency for International Development (USAID) and the International Bank for Reconstruction and Development (IBRD) low lift pumping programs throughout most of south and southeast Asia. Secondly, the pumping systems studied were based on U.S. prices and equipment. Work done by META Systems also attempted to estimate capital costs of low-speed diesel systems constructed in Pakistan and India. Assuming the utilization of low-speed diesel engines sets in pumping applications, the cost of water would be reduced by roughly 40%.[11] The shape of the curve remains the same, however. The META report also suggests that "sewage" pumps have a high potential for application in low head water lifting. These pumps have never been used for irrigation and therefore their economic performance is highly uncertain. The preliminary analyses cited showed costs of low-speed with "sewage" pumps to be roughly one-third those of conventional diesel systems.[12] If this is the case, such systems would be economically attractive to farmers of one or fewer hectares.

Two curves for the cost of water have been shown for pumping experiences in India. These figures, reported in Smith and Allison, are for pump sets (pump and motor) of 5hp and are assumed to be operating on wells of 5m depth.[13] As was the case with the analyses for Chad, the curves show a range of uneconomic operation at farm sizes less than 1.5 to 2 hectares. As can be seen from Figure 2, the least expensive alternative investigated was the electric pumping system in India. The environment within which such electric pumping can occur is extremely limited. Few rural areas in the developing nations receive gridded electrical power or are likely to do so in the near future. In addition, Smith and Allison have calculated the cost of the electrical pumping scheme assuming a flat cost of electrical power at the rate of $.05/kWh, a level requiring significant government subsidy. Small-scale irrigation power requirements do not justify the extension of distribution systems given both the seasonal nature and the low level of rural demand.

However, electrical pumping systems appear to be the most economic of the set of conventional alternatives for the size of the system studied--a significant finding.

Given current traditional and conventional methods of water pumping for irrigation as shown in Figure 2, there are no economically viable alternatives open for the small farmers, those farming approximately one hectare of land. The section which follows discusses the potential for utilizing photovoltaic (solar cell) powered pumping systems to supply water over low lift regimes to small farms. The systems considered were for water lifts of 1.5 and 4.5 meters, a pumping environment common within most deltaic areas. While photovoltaic electric generation systems require a relatively high technology production process, their modularity and lack of moving parts makes them an ideal power source in geographically isolated applications. These characteristics make photovoltaic pumping systems, even at today's relatively high prices, an economically attractive investment for small-scale farmers.

ECONOMICS OF PHOTOVOLTAIC POWERED IRRIGATION SYSTEMS

Before beginning a more complete discussion of the potential economic benefits to the development of photovoltaic powered irrigation systems, it is important to mention briefly the history and projected path of cost decline in solar cell modules. Figure 3 presents the historical and projected cost decline curve for photovoltaic modules manufactured in the United States (note: the price reduction has been brought about by active governmental involvement in technological development and limited commercialization activities). The current price of photovoltaic modules in 1975 dollars is $8 to $10 per peak watt Wp).[14] The work of the Jet Propulsion Laboratories (JPL) of the California Institute of Technology has shown a clear pathway for manufacturing modules in the range of $2 to $3/Wp given current technology and a likely pathway to $.50 given processes now developed. The governmental goals supported by research at JPL indicates that prices in the range of $2/Wp can be reached by 1982 and $.50/Wp by 1986. These cost-reduction estimates for photovoltaic modules become significant in the analysis of the potential for such systems in developing country irrigation applications for two reasons: the first is associated with the U.S. manufacturers' market for photovoltaic systems, and the second is connected with the economic impact of introducing photovoltaic powered irrigation systems into the developing nations themselves.

Studies of the economics of photovoltaic power systems indicate only a limited number of markets for such systems within the United States and other nations with well-developed electric power grids.[15] As a result, much of the early market for photovoltaic power systems will be in remote applications and, in all likelihood, in developing country applications. The irrigation market, discussed in this paper, represents an application which shows a major potential for sales of photovoltaic equipment outside the United States.

The economic benefits which can be seen in the potential development of photovoltaic irrigation systems in developing countries appear to be great even at today's module prices. The lower module costs anticipated by U.S. manufacturers in the near future will make these systems more economical to their adopters. As was discussed earlier in this paper, the approximate value of water for irrigation purposes is between two and three cents (U.S.) per m^3 of water provided. Given the value of water to a farmer, it is possible to calculate the amount that the farmer would be able to pay for water. When this calculation, which was done by Smith and Allison, is assessed for the 1.5 and 4.5 meter lifting regimes, given the assumptions in Table 1, the value of the photovoltaic modules for a 1.5 meter lift is between $8.60/Wp (given a non-module rest-of-system cost of $100) and $7.90/Wp (given a $200 non-module rest-of-system cost). The comparable values for lifts of 4.5m with $150 and $300 non-module (pump, casing, and well) costs would imply values for the modules between a high of $2.75/Wp (U.S.) and a lower value of $1.40/Wp (U.S.).

For purposes of analyzing the cost of water for small-scall farmers in this paper, a 1.5m lift system employing 200 Wp of photovoltaic power equipment, somewhat larger than that actually required, was used (as compared to a 133.3 Wp system in the work by Smith and Allison). In addition, a 4.5 meter lift system, which requires 400 Wp of photovoltaic power equipment, was analyzed for comparative purposes. Such sizes allow for the consideration of 200 Wp modules for the hypothesized microscale pumping system. Given a photovoltaic module available at today's priuces of $10/Wp, the cost of the water pumped would be between 2.7 and 2.9 cents (U.S.) per m^3 for the 1.5m lift, and between 5.4 and 5.6 cents (U.S.) for the 4.5 meter lift (see table 2). Calculations for values of $4.00/Wp (U.S.) would yield costs per m^3 of 1.2 cents (U.S.) for lifts of 1.5m, and 2.3 cents (U.S.) for lifts of 4.5m. These values have assumed a module of 200 Wp would be an optimal size. If the systems

TABLE 1

PERFORMANCE ASSUMPTIONS: PHOTOVOLTAIC POWERED MICROSCALE PUMPING SYSTEMS

Area Irrigated	1 hectare	
Pumping Regimes (Power in Peak Watts)*	1.5 M Lift 4.5 M Lift	133.3 400
Crop	Rice	
Crop Water Requirements	10,000 M^3/ha	
Incremental Crop Production	2.5 Tons	
Value of Incremental Crop	$250**	
System Life	15 Years	
Interest Rate	10%	
Pumping System Efficiency	50%	
Pump plus well costs	$100-$200	

* Given 4.8 watt-hours/peak watt/irrigation day

**It is assumed that 65% of the incremental income is available to pay off the loan.

SOURCE: Adapted from Smith and Allison, Micro Irrigation with Photovoltaics, MIT Energy Laboratory Report, MIT-EL 78-006, Cambridge, MA, April 1978.

required for the 1.5m lift are oversized by a factor of 1/3, and given complete modularity in the photovoltaic portion of the system, costs could be reduced by reducing the effective cell area by 1/3. For the deeper lift of 4.5m, this is not, however, the case, as full module output is required for pumping. There are a series of questions concerning the sensitivity of the results, reported in this analysis, to information not available at the time of this writing. Table 2 summarizes both the current case values in cents/m^3 (U.S.) (cases Ia and Ib and IIa and IIb) and the sensitivity of these analyses to the efficiency of the pumping system (cases IIIa and IIIb). The economic value of the microscale pumping systems is highly dependent upon the cost of the modules. As was shown, at values of $4.00/Wp (U.S.), cases Ic and Id, the 1.5m lift is more than economical for farms of 1 hectare, and the 4.5m lift requirements are at least marginally economic (cases IIc and IId). The anticipation of the U.S. governmental photovoltaic program is the achievement of these system costs during the next two to three years.

As was shown, the system costs themselves are not highly sensitive to the cost of the non-module components, such as well casings and pumps, because non-module components make up a relatively small proportion of the total cost. Non-module component costs are not expected to dominate in the decision to buy or not to buy a pumping system. However, were pumps not available at these prices and efficiencies, these components would become more signigicant parts of total cost.

The area of sensitivity most crucial from the viewpoint of the analysis carried out in this paper is the assumption of a total pumping system efficiency of 50 percent. Considerable research is required to

TABLE 2: VALUE OF WATER PER CUBIC METER PUMPED WITH A PHOTOVOLTAIC POWERED MICROSCALE IRRIGATION SYSTEM

Cases	Pumping Efficiency 50%						
	Lift(M)	Wp	$/Wp	Non-Module Costs	Total Cost	Annualized Cost	¢/M^3
Ia	1.5	200	10	100	2100	279.1	2.8
Ib	1.5	200	10	200	2200	289.2	2.9
Ic	1.5	200	4	100	900	118.3	1.2
Id	1.5	200	4	200	1000	131.5	1.3
IIa	4.5	400	10	150	4150	545.6	5.4
IIb	4.5	400	10	300	4300	565.3	5.7
IIc	4.5	400	4	150	1750	230.0	2.3
IId	4.5	400	4	300	1900	249.8	2.5
Sensitivity of Results assuming pumping efficiency of 25% rather than 50%							
IIIa	1.5	400	4	100	1700	223.5	2.2
IIIb	4.5	800	4	150	3350	440.4	4.4

* For financial and system assumptions not included in this table, see Table 1

either discover existing pumping systems which will deliver efficiencies on the order of 50 percent or to develop systems with this characteristic. The significance of a 50% efficiency cannot be overstated. If efficiencies of the pumping systems were only 25%, the required cost would effectively be doubled, given the small proportion of the total cost which can be accounted for by the cost of the non-module portions of the total irrigation system (see Table 2).

Lastly, the sensitivity of farms of less than one hectare in total size to the value of irrigating their land was evaluated. It is difficult to argue for perfect modularity in the development of photovoltaic powered irrigation systems. If there were no economies of scale in production, then it would be possible to have a nearly flat curve for pumping systems in Figure 2. We have assumed, as was assumed with the other systems discussed herein, that there are some economies in production, and as a result, the prices would increase as the farm size decreased to 1/2 hectares. The curve represents a median value. It is unlikely that the cost to the farmer of 1/2 hectare would be the same as to a farmer of one hectare, i.e., that there are no scale economies. It is equally unlikely that given the basic modularity of the photovoltaic power system there would not be systems available smaller than 200 Wp. Figure 2 presents a cost per m^3 of water to the farmer of 1/2 hectare equal to 1.5 times that to the farmer of 1 hectare.

SUMMARY

It can be seen that the technology of photovoltaic-powered microscale irrigation systems may offer a highly economic source of water to farmers with extremely small plots of land, those less than 2 hectares. These systems have not been fully tested, and as a result, there are at present three major areas of uncertainty which must be resolved before their effective entry into the market. The most significant of the uncertainties concern the cost of the photovoltaic modules themselves. As was discussed, it is likely that future anticipated cost reductions for photovoltaic systems by U.S. manufacturers will more than accomplish the reductions required for entry into this market. The second uncertainty is more critical since little is known concerning available pumping systems than can achieve relatively high levels of efficiency at these scales. While this analysis has assumed 50%, a value that may be optimistic, additional testing and research is required to attain this level of efficiency. The third and final uncertainty relates to the institutional structure within which such a development will be introduced. The systems themselves will be capital-intensive, requiring virtually no operating and maintenance costs. For the systems to enter the market, an active and well-developed rural credit system and a willingness on the part of lending institutions to finance such systems will be required. For the lender to be an active participant in the expansion of the use of photovoltaic powered microscale irrigation systems, these systems must leave the laboratories and be demonstrated on agricultural experiment stations and on model farms in the deltaic regions. The competitive advantage of such systems shown in Figure 2 requires proof in the marketplace.

FOOTNOTES

1. For a more complete discussion of the impact of the "Green Revolution" on farming in the Punjab region of Pakistan see: C. H. Gotsch, "Technological Change and Private Investment in Agriculture: A Case Study of the Pakistan Punjab" (Ph.D. Dissertation, Harvard University, 1966).

2. For East Pakistan, see contribution by J. W. Thomas in G. Papanek, ed., Development Policy II: The Pakistan Experience (Cambridge: Harvard University Press, 1971).

For Vietnam, see R. L. Sansom, Economics of Insurgency in the Mekong Delta of Vietnam (Cambridge: MIT Press, 1970), esp. chs. 7, 8.

3. Ibid., pp. 173, 174.

4. D. V. Smith and S. V. Allison, Micro Irrigation with Photovoltaics (MIT Energy Laboratory Report MIT-EL-78-006, April 1978).

5. Personal communication with Dr. James Gavan, International Food Policy Research Institute, Washington, D.C., May 1978.

6. Alan Strout, Projecting Agricultural Crop Supply from Cross-Country Data (Mimeo, MIT, June 1978).

7. Sansom, op. cit., ch. 8.

8. Ibid., p. 169.

9. The analyses for human, animal, and conventional water lifting systems have been adapted from work by Tabors in Metasystems, Inc., Analysis of "Revelle" Polders Development Scheme and Design for a Long Range Lake Chad Basin Study (Working Draft Report, Cambridge, MA, 1974), pp. 52-109. Values reported are in U.S. dollars. Dollar values from META Systems are 1973/74, those for India for 1975.

10. Calculations for Chad are from META Systems, op. cit. Those for India are from Smith and Allison, op. cit., pp. 10-11.

11. META Systems, op. cit., pp. 75-81.

12. Ibid.

13. Smith and Allison, op. cit.

14. A peak watt is the potential energy which can be generated from a photovoltaic device at 1 atmosphere at 12 noon given a cloudless sky. The analysis which follows assumes that in most of the areas requiring irrigation, one peak watt (Wp) will generate 4.5 watt hours per day.

15. See P. Carpenter and G. Taylor, An Economic Analysis of Grid-Connected Residential Solar Photovoltaic Power Systems (Cambridge: MIT Energy Laboratory Technical Report MIT-EL 78-007, May 1978).