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Investment in Water-Saving Irrigation Options under Uncertainties – A Comparative Analysis

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Abstract

The agricultural sector of Pakistan consumes 96 percent of the country's available fresh water resources. With a population of 187 million and increasing at an annual growth rate of 1.57 percent, the fresh water resources of the country will face severe stresses in the coming years, affecting its food security. At the same time, there is uncertainty prevailing in the region about climate change, timing and intensity of rainfall, flood and drought events, coupled with glacial melt and unresolved issues pertaining to trans-boundary water resource management. Under these circumstances, investment in agricultural practices that ensure crop productivity and water conservation are critical to Pakistan's food security. This study focuses on a sub-region of Punjab in Pakistan, where wheat is grown using flood irrigation. It examines whether an investment into water-saving irrigation options, such as canal lining, dredging, water saving irrigation technologies, and on farm water storage are feasible options to improve profits of the farmers. Irrigation in Pakistan is supplemented with low quality groundwater, which at times leads to very low yields per unit of water. By comparing the discounted cash flows under each of these options, this study investigates the best investment decisions on the part of the farmer and policy makers. This study also looks at the benefits of crop diversification and water markets, to examine whether these options would lead to higher profitability, hedging of risks and productivity in the study area. The economic analysis is complemented with real options analysis, and where applicable, sensitivity analysis to determine the minimum yield increases required to break even.

Key words: Canal lining, desilting, dredging, sprinkler irrigation, water storage, net present value, real options, water markets, crop diversification.

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Nomenclature

Acronyms

IWMI – International Water Management Institute

IIMI – International Irrigation Management Institute

IMT – Irrigation Management Transfer

FO – Farmer Organizations

PID – Provincial Irrigation Department

PIDA – Punjab Irrigation and Drainage Authority

AWB – Area Water Board

IBIS – Indus Basin Irrigation System

Conversions

1 acre = 0.404685642 hectares

1 kilogram = 0.001 metric tons

1 mound = 40 kg

1 irrigation unit = three acre inches of water

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1 Introduction

This study builds on (Absar, 2009)[1] which finds that the further away you are from the head of a canal, distributary or watercourse, the worse off you are in terms of crop yields and profits. The results suggest that where canal water is available, the farm inputs are conjunctively used by the farmers but where canal water is not available, groundwater is substituted and there is a subsequent decrease in the use of all other inputs. The farmers located at the head and middle reaches use more canal water in conjunction with the inputs to generate higher returns, whereas the farmers at the tail-end reaches rely more on groundwater and get lower returns. This may either be due to the lower quality of groundwater[2] or the fact that in a deficit irrigation system, farmers tend to under-irrigate and put both crop quality and returns at risk[3]. Currently, the farmers are paying an annual water tax of $1.56 per acre regardless of how much water they obtain from the canal and what they decide to grow on their land. The farmers are also faced with a much higher price of $13.90 per acre for extracting groundwater which is of much lower quality than the canal water.

Nevertheless, tail-end farmers, whether located at the primary, secondary or the tertiary level in a multi-tiered irrigation network in Punjab, are a marginalized segment in terms of water distribution and availability. They have not voluntarily selected the location of their farms nor are they flexible to move within the network. The tail-end farmers in our sample are assumed to have access to the same resources, prices, knowledge and possess the same skill set. The only factor affecting their yield is their location vis-à-vis

[1] Absar, M., Choice of Farm Inputs in Response to Uncertain Irrigation Supplies in Pakistan, Master's Thesis, Yale School of Forestry and Environmental Studies, 2009 (Manuscript under preparation)

[2] As determined by Latif (2000) who made use of the same data set as this study. Latif, M., 2007. Spatial productivity along a canal irrigation system in Pakistan. Irrigation and Drainage. 56: 509-521.

[3] Perry, C. J., and S. G. Narayanamurthy. 1998. Farmer response to rationed and uncertain irrigation supplies. Research Report 24. Colombo, Sri Lanka: International Water Management Institute.

the primary canal. That is why this study is focused on looking at investment in water-saving irrigation options under uncertainties by the tail-end farmers, to identify possible measures to adapt to prolonged water shortages. These options include lining of the secondary canals, dredging of secondary canals, water saving irrigation technologies and on-farm water storage to augment current water deliveries.

The methodology used to study these options is the comparison of net present values (NPV) of discounted cash flows under each option. Where applicable, real options analysis and decision trees are used to study the impact of uncertainty on the value of the options faced by the farmers in multi-period settings. To overcome the limitation of the literature and the available data, sensitivity analysis is carried out to analyze the robustness of the results.

In addition, this study explores the benefits of diversification, particularly the use of alternate crops. This is done by determining a crop portfolio derived from a covariance matrix based on the crop prices for each of the crops selected in a crop mix. This study also looks at the applicability of water markets to the study area and the possibility for trading of canal water within the system to shift it towards uses that yield higher marginal returns. Furthermore, this study looks at the structural changes in the management of the canal system to observe how they help to reduce unprecedented water losses such as water theft, through devolution of power.

The study is structured as follows. Section 2 describes the background and objectives of this study. Section 3 introduces the options that are under investigation and the pros and cons of each of them as described in the literature. Section 4 delineates the quantitative details of the methodology used to study each option. The study draws to a close with a discussion and conclusion section, summing up the results and recommendations derived from within. Additional methodologies study the benefits of crop diversification and derive a crop portfolio for the study area in Appendix A. Appendix B delineates the water market structure existing in Pakistan and also determines the equilibrium water price for the canal water in the study area. Appendix C elaborates how devolution of power can help prevent water theft.

2 Study Background

This study is focused on a sub region of Punjab, located close to the eastern border of Pakistan. This region is arid and highly dependent on irrigation water for wheat cultivation. The primary data acquired for this study is from the command area of a primary canal called the Main Branch Lower canal (MBL), which branches from the Bambanwala Ravi Bedia Depalpur (BRBD) link canal which is also a primary canal. Six secondary canals are selected along the MBL: two each at the head, middle and tail reaches of the canal. Further, nine tertiary canals are selected, three each at the head, middle and tail sections of each secondary canal, making a total of 54 watercourses. The farm level data is collected from farms located at the head, middle and tail sections of each watercourse, rendering a total of 486 farmers[4]. This cross sectional data comprises of farm inputs such as fertilizer, pesticides, harvesting, threshing, labor and other miscellaneous input expenses. The data also includes information on water charges for both canal and groundwater and the number of flood irrigations applied from each type of water source[5]. All the costs are in rupees normalized per acre of land, but for this study, they are converted to US$, using the exchange rate of 1US$/PKRs.86.07. The wheat production is measured in mounds[6].

The data is complemented by the results of an extensive literature review to determine the advantages and disadvantages of each of the studied investment options. The available literature looks at each of the options in great detail but there are very few studies that quantitatively compare the feasibility of each of these options. This study also compiles and collects secondary data on the investment costs for each of the water saving irrigation options, calculates the Net Present Value (NPV) of their revenue streams and converts them to a comparable format to help in decision making, both for the farmer and the policy makers.

3 Qualitative Analysis of Options Available to the Tail-End Farmers

This section explores several options available to the tail-end farmers either through government intervention or as an investment option for the farmer, namely: lining of the secondary canals, dredging of secondary canals, water saving irrigation technologies and on-farm water storage. This section also introduces water markets and trading, water theft reduction through devolution of power and the benefits of diversification through the cultivation of alternate crops.

3.1 Lining of the Secondary Canals

Canal lining in Pakistan involves a single brick lining plastered with 1.25cm of thick cement applied on hand compacted earth to both the channel floor and the side walls of a canal. Partial lining involves lining the lower third of a channel leaving the upper two

[4] The primary data in this study was obtained from the Centre of Excellence in Water Resources Engineering, University of Engineering and Technology, Lahore, Pakistan and was collected by Dr. Muhammad Latif and his graduate student Zakaria.

[5] In addition, the data includes total expenses incurred, total income from farm production and bi-products, and net revenues.

[6] 1 mound = 40 kg

thirds unlined[7]. As described earlier, there are three tiers to the irrigation system in Punjab. The studies conducted by IWMI (International Water Management Institute formerly known as the International Irrigation Management Institute) have established that major differences in distribution equity prevail between the discharges at the head and tail-ends. Experiments conducted in brick lining have focused on lining the tail-end of the canal. Prior to any lining, desilting of the upper two thirds of the channel is carried out to improve the hydraulic conditions of the canal[8].

3.1.1 Advantages of Canal Lining

There are benefits to lining of canals in some agricultural settings. Lining of canals is promoted as a long term solution to seepage and conveyance losses. It improves hydraulic conveyance efficiency and reduces the contribution of canal water to an increased water table. Lining of canals stabilizes the canal cross-sections that results in more manageable head discharge relationships. It may also reduce the maintenance inputs required on a recurrent basis. However, all these benefits require an in-depth understanding of the existing levels of canal performance and significant capital and investment costs, either at the time of initial construction or when lining is retrofitted to the original construction[9].

3.1.2 Disadvantages of Canal Lining

With the lining of the canals the discharge into the secondary canals increases, which can also be a result of extensive desilting and bank improvement in the upper reaches of the canal prior to lining. Murray-Rust and Van der Velde (1993) have studied partial lining of canals which reveals significant improvement in the delivery performance ratio at the tail-end, but no significant change in discharge after the lining was put in place[10]. After lining the lower third of the canals, when the canal discharge was at or above design, the difference between the head and tail reaches was not significant but when the canal head fell to 70–80 percent of design discharge, the head end areas received significantly more water. There is also a considerable degree of unreliability associated with the canal lining, if there is a degree of variation between daily discharges over a period of several months in a given canal, the lining of canals will aggravate the

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[7] Murray-Rust, D. H. & Van der Velde, E. J. (1994) Changes in hydraulic performance and comparative costs of lining and desilting of secondary canals in Punjab, Pakistan. Irrigation and Drainage Systems 8: p. 137–158.

[8] Murray-Rust, D. H. & Van der Velde, E. J., (1993) Impacts of Physical and Managerial Interventions on Canal Performance in Pakistan: A Review of Five Years of Field Research Studies. In International Irrigation Management Institute (IIMI). Advancement in IIMI's Research 1992. A Selection of Papers Presented at the Internal Program Review (pp. 79 - 112). Colombo, SriLanka: IIMI.

[9] Murray-Rust & Van der Velde (1994), op.cit., p. 140.

[10] Murray-Rust & Van der Velde (1993), op.cit., p. 85.

discharge variation, affecting reliability of water deliveries, especially when the canal heads fall below the design level[11].

Partially lined canals require desilting after two to three years of usage in order to allow water to continue to the tail-end reaches. Lining does not solve the problem of inequity created by sedimentation in the upper reaches of the canal. With periodic maintenance of lined canals, their benefits may last up to five years[12]. The material used to line the canals varies from place to place and so does their functional life length. In the worst case scenario, if lining does not work for its intended period, the tail-end farmers cultivate a reduced fraction of their holdings. Moreover, the tail-end outlets may need to be shifted upstream causing a reduction in the command area and *abiana*[13] allocating more money for relocation[14].

Lining can only be effective if the process is well controlled, managed and maintained. Bridges are built for cattle to cross over, cracks are periodically filled in, weed growth is prevented, and disturbances due to theft of bricks from the lined sections and tampering with outlets during the construction phase are prevented. Canal lining cannot be justified in terms of the value of water saved (capital cost involved in saving it) if it is charged at the rate of the *abiana* and can only be justified if the water is priced at the value paid by the farmers for groundwater use, if the life length of the lining is in the order of 10 years or more and if the water savings in the canal are about 15 percent of the design discharge[15]. Under these circumstances, the *abiana* rate would have to greatly increase to repay the investment which may be politically impossible. In this case, lining would have to be a subsidy rather than an investment and would be sustainable only if the lining conditions were significantly improved[16]. This study will look at investment in extensive canal lining i.e. the costs involved in brick lining the entire stretch of a canal.

3.2 Dredging of the Canals

Dredging of the canal is done by two methods; major desilting or selective desilting. Major desilting involves removing sediment from the canal and restoring its initial design cross-section to improve hydraulic conditions of the channel. In the upper half, the channel bulldozers and excavators are used while in the lower half, desilting is carried out by hand using locally available man power[17]. Selective desilting is removal of sediment only from those sections of the canal where the bed elevation is unduly

[11] Murray-Rust & Van der Velde (1994), op.cit., p. 145.
[12] Murray-Rust & Van der Velde (1994), op.cit. p. 149.
[13] Annual water charge collected by the government for the allocation of canal water
[14] Murray-Rust & Van der Velde (1994), op.cit. p. 149.
[15] ibid
[16] ibid.
[17] Murray-Rust & Van der Velde (1994), op.cit., p.141

high[18]. This method is less costly and requires less labor inputs. Since persistent tail-end problems result from sediment accumulation in the head reaches of the canal, selective desilting is largely carried out in this section.

3.2.1 Advantages

Only a modest amount of desilting is required to greatly improve tail-end conditions and major desilting significantly helps in delivering the design discharge almost at the designed water surface elevations[19]. It is observed that before desilting, the tail-ends are largely dry whereas post desilting, the tail-end conditions match those of the head and middle reaches. Also, a similar improvement is observed at the watercourse outlets with respect to variability of discharges. Desilting also has a positive impact on the reliability of water deliveries to the farmers. Compared with other options desilting requires the least financial and labor inputs.

3.2.2 Disadvantages

The economic life length of major desilting interventions is up to five years. After this time the benefits decline and have a much more limited impact on the economic analysis. The benefits of selective desilting may last up to two years. This short life span makes it imperative to reinvest in desilting periodically to maintain the design discharge[20].

3.3 Water Saving Irrigation Technologies

Pressurized irrigation systems have better uniformity and higher application efficiency, giving rise to higher crop yields. In Pakistan the yield per unit of water is the lowest in the world[21]. Experimental research on drip and sprinkler irrigation conducted so far in Pakistan shows that these technologies not only result in significant water savings on the farm but also lead to higher crop yields as compared to surface irrigation methods. The drip and sprinkler irrigation systems give satisfactory results in the desert and hilly terrains and can also be used with gravity flow systems where a hydraulic head is available, reducing the initial costs[22]. This study looks at two water saving irrigation systems; drip irrigation and sprinkler irrigation. In this section, the advantages and disadvantages of both systems are studied. Sprinkler irrigation is explored further in Section 4 to determine whether investment in such a system would be feasible for the study area because sprinkler systems are more relevant to wheat production.

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[18] ibid,
[19] Murray-Rust & Van der Velde (1993), op.cit., p.93
[20] Murray-Rust & Van der Velde (1994), op.cit., p. 149.
[21] Alam, M. M., Bhutta, M. N. Azhar, A. H. (2003) Use and Limitations of Sprinkler and Drip Irrigation Systems in Pakistan. Pakistan Engineering Congress, 70th Annual Session Proceedings.
[22] ibid.

3.3.1 Drip irrigation

A drip irrigation system uses a network of pipes ending with small emitters to provide water directly to the plant roots. The pipes can either be laid out on the soil surface or buried. The system is usually designed to water crops at intervals according to the needs of the crop being grown[23].

3.3.2 Advantages

Drip irrigation needs high investment costs but they are compensated by water savings and an increase in production especially in those canals where surface water is available for a few consecutive months. Drip irrigation may alleviate poverty by boosting yields and thus income and also having the co-benefit of reducing the ill effects of over irrigation. Excess water or waterlogging affects soil aeration and hence plants roots do not grow properly. Waterlogging is often accompanied by salinity as waterlogged soils prevent leaching of the salts imported by the irrigation water, affecting the pH of the soil. New and ongoing irrigation projects can benefit greatly from the use of water saving technologies. Saline water can also be used in the drip irrigation system as the salt is accumulated only at the surface of the periphery of the wetting zone and does not affect the growth of the crop and maintains constant soil moisture in the root zone[24].

The water use efficiency is 90–95 percent as compared to only 40–50 percent in the surface irrigation due to the partial wetting of the soil volume, maintained soil moisture content, reduced surface evaporation, decreased runoff and controlled deep percolation losses. Water productivity in project areas is expected to be enhanced by 30–100 percent due to better water management and production practices. There are savings in terms of labor, as labor is only required to start or stop the system. And due to the high irrigation efficiency only little time is required to supply the desired quantity of water thus saving energy. Cropping intensity can be increased for the existing commands and new areas can be brought under command for the new schemes[25].

Drip irrigation works well on poor soils, prevents weed growth and reduces operational costs associated with weed prevention like spraying of weedicides and pesticides etc. There is reduced loss of nutrients under drip irrigation due to localized placement; fertilizer efficiency can be improved significantly. Also under drip irrigation there is no soil erosion nor is there any need for extensive soil preparation, thus cutting down on labor and operational costs[26].

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[23] Booher, L. J. (1974) Surface Irrigation. Agricultural Development Paper No. 95. FAO, Rome.
[24] Alam et. al., op.cit., p. 88.
[25] ibid.
[26] ibid.

3.3.3 Disadvantages

The rate of success for these irrigation systems has been low because of the low cost of canal water, lack of confidence amongst farmers to operate and maintain these systems, high initial costs and lack of support services. Drip irrigation systems require extensive maintenance as the emitters can get clogged with time. The pipelines can leak or the tubes can crack. The system needs to be protected from farm animals and on-farm activities and may require regular replacement and maintenance. The complex equipment and maintenance requirements increase the initial investment costs and the operational costs of this system and may not be an effective choice for the small to medium sized farms. Highly skilled labor is required for designing the installation, management and the operation of the system[27].

3.3.4 Sprinkler irrigation

Sprinkler irrigation is a method of distributing water in pipes under pressure and spraying it into the air so water falls to the ground like natural rainfall. The costs of three types of sprinkler systems are considered in this study; the center-pivot, rain-gun and the linear move sprinkler systems, as they have recently been subsidized by the government of Pakistan and are locally manufactured or acquired in collaboration with the private sector[28].

3.3.5 Advantages

As timing of water application is important for crop yields, sprinkler systems allow for timely irrigation of a few centimeters of water at critical crop growth stages, which can double the yields. Most of the system components of sprinkler systems have been successfully manufactured in Pakistan using locally available materials and technologies. In areas where labor and water costs are high due to labor intensive crops and heavy reliance on groundwater for irrigation, sprinklers can be the most economical way to apply water and can be used in conjunction with a gravity flow system. The same equipment can be used for multiple uses like irrigation, crop cooling, frost control, spraying of pesticides and fertilizers etc. These systems have shown water savings of up to 57 percent and an increase in productivity per unit of water of as much as 125 percent for wheat crop in Pakistan[29].

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[27] Alam et. al., op.cit., p. 90.

[28] Pakistan Agricultural Research Council (PARC), (2010) Water Conservation and Productivity Enhancement through High Efficiency Irrigation Systems (Revised). Ministry of Food and Agriculture. Islamabad: Planning Commission, Government of Pakistan.

[29] Alam et. al., op.cit., p. 90.

3.3.6 Disadvantages

Sprinkler irrigation systems have high initial investment costs in addition to operation and maintenance expenditure. These systems also require skilled labor to maintain and operate. Therefore high training costs need to be incurred prior to the installation of this system[30].

3.4 On Farm Water Storage

With the surface irrigation system working at 40 percent water efficiency, excess water can be harnessed from the months with surplus water available and stored for months with low water supply. Farms at times may receive even less than 50 percent of their promised share of canal water turn[31]. Water supply at the critical stages of crop growth is essential for a good yield and at times availability of adequate supply of canal water is uncertain. Application of water at the critical stages of crop growth affects the crop yield. Adequate water supply at these critical stages can lead to a 6 percent increase in yield[32]. Under such circumstances, excess water from the canal, ground or rainfall can be stored in on-farm storage reservoirs. According to the study conducted by Choudhry et. al, (2000), surplus irrigation water occurs mostly during November through January or from August through September and some regions of northern Punjab receive more rain in the winter and summer months than the rest so the rain water can be harvested and stored[33].

An on-farm reservoir can be used in rain-fed areas, in conjunction with a gravity flow system or a pressurized irrigation system such as a sprinkler system. The challenges involved with this system include identification of an ideal location for the reservoir in a farm setting, for the farmers to agree on a method of sharing the water from the reservoir and the cost of construction and maintenance of the storage structure[34]. According to the Pakistan Agricultural Research Council (PARC), the storage capacity of a reservoir should be about 400 m^3 per hectare in a seven-day rotation interval. Most reservoirs are excavated to allow gravity flow from the canal. The need for lining depends on soil conditions. In heavily textured clay soil, good compaction may be sufficient. Percolation losses of up to 5 cm per day may be acceptable. If the percolation losses are higher, lining is required. There are different lining methods, the least expensive lining is probably polyethylene (PE) liner covered with about 30 cm earth or stone pitching with concrete grouting where stones are locally available. More

[30] PARC, op.cit., p. 10.
[31] Choudhry, M. R., Iqbal, M., Awan, M. N. (2000) Farmers Response to Farm Water Storage Reservoirs to Supplement Irrigation at Watercourse Command. Pakistan Journal of Agricultural Resources. Vol.16, No.1, p. 45–49.
[32] ibid.
[33] ibid.
[34] ibid

expensive are polypropylene and geo-synthetic liners that can be used in exposed installations[35].

3.5 Benefits of Crop Diversification

Crop diversification involves moving away from monoculture and growing a variety of crops in a given season on a single land holding. Since product prices of each crop vary in the market, the farmer would benefit if he has a mix of crops to sell at the end of the season by hedging against any price fluctuations. Growing diverse varieties enables the grower to stay in the marketplace longer and compensates for negative market price fluctuations. Crop diversity extends seasons even further. A cropping system that includes annual and perennial crops can extend employment to a year-round basis. Crop diversification is discussed further in Appendix A.

3.6 Water Markets and Trading

The timely delivery of surface irrigation water is crucial to crop yields, which is why farmers resort to extracting groundwater or practicing deficit irrigation in Pakistan. The cost of extracting groundwater is ten times that of canal water. The canal water is shared through time sharing which means that each farmer has to wait for his turn in line to get his seasonal allocation which may or may not come at a critical period of the crop growth cycle. To solve this problem, many countries around the world engage in water trading which involves establishing a water market, where demand and supply determine the equilibrium price for the canal water, at which it is traded to ensure its most cost effective usage, i.e. where the marginal returns of each unit of water used are higher. This process is usually overseen by the local water utilities to make sure transactions, allocations and water rights are traded fairly. In Pakistan at present there is no formal water market, however, water does get traded amongst the farmers in a very informal fashion, without the involvement of any government body or an overseeing authority. The current trading practices in Pakistan are explained in detail in Appendix B, in addition to exploring the application of a water market and determining the equilibrium price of the canal water for our study area.

4 Quantitative Assessment and Uncertainty Analysis of the Options

This section provides an overview of the methodology used to study the water saving irrigation options discussed in Section 3. The core methodology used to study and compare investments in canal lining, desilting, sprinkler irrigation systems and on-farm

[35] PARC, op.cit., p. 16.

water storage is the calculation of discounted cash flows for 25 years (physical lifetime of a canal structure without requiring any major refurbishing) and comparing the Net Present Values (NPV) of profit streams for each of these options. A discount rate of 10 percent[36] is used throughout the analysis[37]. Where applicable, real life examples are illustrated using flow diagrams, decision trees and real options analysis.

4.1 Lining of the Secondary Canals

For the brick lining of the canals, only the option of extensive lining is considered[38] where two investment options are studied; (1) the government is making the initial investment of lining the canals and the farmer is only paying for the annual operation and maintenance of canals, and (2) the farmer is making the initial investment and also covering the operational and maintenance costs. Once lining is in place and if flow variation exists in the system, there is a 40 percent chance that the head discharge of the canal distributary would fall below the design level and the tail-end farmer will not get an increase in yield and there is a 60 percent chance that the head discharge would be at or above design level leading to an observable increase in yield[39]. These percentages are translated from the literature where based on the fact that the discharge at head can be either above or below the design level affecting discharge and yields at the tail-ends of the canal. If regular maintenance is undertaken, the chances of head discharge being above the design level are higher than not, which is why a probability of 0.6 is used as opposed to 0.5 for this analysis. A sensitivity analysis is carried out to determine the minimum percentage increase in yield required by the farmer under each option to break even in terms of profits.

4.1.1 Methodology

To assess the feasibility of investment in extensive canal lining, the NPV of the profit stream for 25 years was calculated for the two instances. The cost of investing in extensive lining is \$61.02/acre[40] and the cost of maintaining the lining annually is \$2.02/acre, which primarily involves major desilting of the canal. The life length of a

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[36] A large number of similar research uses a discount rate of 10 percent, see e.g. Murray-Rust, D. H. & Van der Velde, E. J. (1994) Changes in hydraulic performance and comparative costs of lining and desilting of secondary canals in Punjab, Pakistan. Irrigation and Drainage Systems 8: pp. 151.

[37] According to Murray-Rust & Van der Velde, the actual cost of capital is significantly more in Pakistan therefore higher values of discount rate of 15 percent and 20 percent can also be used.

[38] Extensive lining is considered because we would like to calculate how much it would cost to line the entire length of the channel as opposed to partial lining which involves lining only the lower third of the channel.

[39] Murray-Rust & Van der Velde, op. cit. pp. 144.

[40] The investment and maintenance costs of lining and desilting were taken from Murray-Rust & Vander Velde and adjusted for the dollar value today.

canal lining is five years[41], this means that after every five years, the canal is re-lined extensively and the same initial cost is incurred.

The profit for a crop-specific increase in yield is calculated by the following formula:

$$\pi = Y_W * (R - C_f - C_v - C_w)$$

Where $\boldsymbol{Y_W}$ is the total units of yield; which is also a function of the water type used, where groundwater typically leads to lower yield increases than canal water[42], $\boldsymbol{R}$ is the revenue per unit of yield, $\boldsymbol{C_f}$ is fixed cost per unit of yield, $\boldsymbol{C_v}$ is the variable cost per unit of yield and $\boldsymbol{C_w}$ is water cost per unit of yield. The fixed costs comprise of land preparation and other miscellaneous costs; variable costs include fertilizers, pesticides, harvesting and labor costs. The water cost per unit yield is made up of the average cost of the canal and groundwater used per unit yield. The fixed costs, variable costs and water costs remain fixed throughout the analysis and are taken as the average of the costs faced by the farmers located at the channel tail and watercourse tail, and those at the channel head and watercourse tail respectively, in order to capture the difference in cost between the farmers at the channel head and the channel tail. The profit is then used to calculate the NPV of future profits of a farmer if he decides to invest in canal lining (NPV_L) and compared with the NPV of profits if there is no investment, or the baseline (NPV_B). Given that the probability that the lining does not drop below design is 0.6, the expected NPV of profits on extensive canal lining is given by:

$$\textbf{Expected Profit} = (\boldsymbol{0.6 * NPV_L + 0.4 * NPV_B})$$

If the discharge at the head-end is above the design level, the tail-end also receives discharges at the design level and increases in yields are observed[43]. In order to find out the minimum increase in yield required to render lining as a viable investment option if the farmer is paying the initial investment cost, a sensitivity analysis is carried out, which reveals that an increase in the yield of at least 12 percent is required to break even. The present value from lining (if it works) is denoted by NPV_L, which with an expected 12 percent increase in yield is $244.14. This is slightly greater than the baseline present value (i.e. without lining), NPV_B, of $239.24. However, if the

[41] Murray-Rust & Van der Velde (1994), op.cit., p.148.
[42] Latif, op.cit., p. 510.
[43] Murray-Rust & Van der Velde (1994), op.cit. pp.144

government is making the initial investment in canal lining, then the farmer only requires an increase in yield of 1 percent to get a NPV_L of $313.92, which is much higher than the NPV_B of $239.24. Comparing the NPVs of investing in lining either by the farmer or the government suggests that lining would pay off only if the government makes the initial investment of extensive canal lining and repeats every five years to maintain the flow above design level.

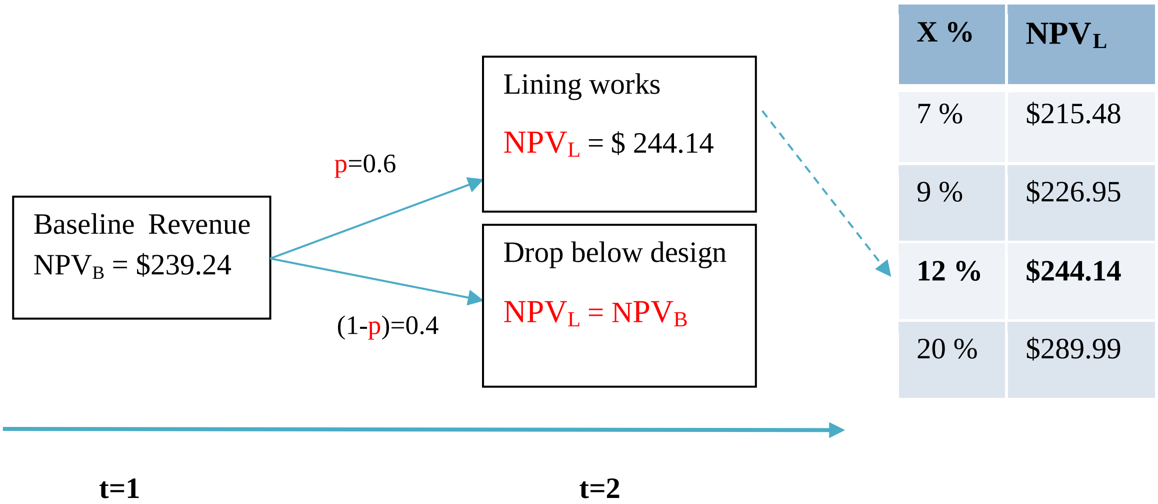

Figure 1: Private investment in canal lining: A Simple Illustration

If the farmer invests in lining, he would have to ensure a yield increase of at least 12 percent, given that the head is above the design level, in order to break even and above 12 percent in order to raise his overall revenues. The diagram in Figure 1 illustrates the profits of the farmer if he invests in a canal lining and also pays for the annual maintenance. The odds that the lining will improve crop yield and thus raise revenues, can be improved by spending on annual maintenance of the canal. Other factors causing variability in the channel flow are beyond the scope of this paper.

4.2 Desilting

For desilting of the secondary canals, only the option of major desilting is studied. Desilting is a very lucrative option if the initial investment is done by the government or the farmer and the maintenance is covered by the farmer every year. The farmer makes higher profits in each case. The underlying assumption here is that the farmer is getting the same yield as the head end farmers because desilting will make the water delivery more equitable, even selective desilting in the upper reaches of the canal has significant beneficial impact on distribution equity at the tail-end[44].

[44] Murray-Rust & Van der Velde (1993), op. cit., p. 85

4.2.1 Methodology

To assess the viability of investment in major canal desilting, the net present values (NPV) of the revenue stream for 25 years was calculated for two instances; (1) where the government is making the initial investment and the farmer is only paying for the annual selective desilting of canals, and (2) where the farmer is making the initial investment and also covering the operational and maintenance costs. The cost of investing in major desilting is $3.57/acre and the cost of annual maintenance is $0.95/acre, which primarily involves selective desilting of the canal. The life length of major canal desilting is 5 years provided that the canal is maintained annually, this means that after every five years the entire canal length is dredged and the same initial cost is incurred[45]. According to Van der Velde & Murray-Rust (1994), after major desilting of the canal, the farmer would get the same amount of water, and hence the same yields as the farmers at the head end of the canal, as desilting will make the water delivery more equitable. This increase in yield is calculated to be approximately 14 percent for the study area. The profit for a 14 percent increase in yield is calculated by the same formula as the one used for canal lining (see section 1.1.1).

If the farmer invests in major desilting by incurring both the initial costs and the maintenance costs, the net present value of his profits (NPV_D) is $456.07, which is $216.83 higher than the NPV_B of $239.24. However, if the government makes the initial investment and the farmer only maintains by doing selective desilting annually, the NPV_D for the farmer is $472.46 which is $233.22 higher than the NPV_B. Hence investment in desilting, whether done entirely by the farmer or the government, pays off with higher profits in the long-run.

4.3 Sprinkler System

The initial cost of installing a sprinkler system is very high and the tail-end farmers cannot afford to cover this cost on their own given their meager earnings. Since 2010 the Pakistani government has been providing a subsidy[46], which covers approximately 90 percent of the initial investment cost and the farmer pays a fixed share of $58.19 per acre. Depending on whether the farmer chooses to install the Rain Gun, Center Pivot or the Linear Move sprinkler system, 20 percent of the cost is covered by the provincial government while the rest is paid by the federal government[47]. The initial investment costs vary from $465.49 per acre for the rain-gun sprinkler system to $698.25 per acre for the center pivot or the linear move sprinkler systems. To simplify, the average of the two cost figures, $523.68 per acre, was used to calculate the NPV of the revenue stream

[45] Murray-Rust & Van der Velde (1994), op. cit. p. 148
[46] PARC., op.cit., p. 13.
[47] ibid.

for 25 years, if the farmer invests in a sprinkler system. For the sake of comparison, the case where there is no subsidy is also considered, where the farmer has to pay the entire initial cost of investing in a sprinkler system. In the latter case, the farmer has to pay an average cost of $581.81 per acre.

4.3.1 Methodology

To evaluate the feasibility of investing in a sprinkler irrigation system, the net present values (NPV) of the revenue stream for two instances; (1) where the government provides a subsidy and the farmer only pays $58.19 per acre in addition to the operational and maintenance costs, and (2) where the farmer makes the initial investment and covers the operational and maintenance costs. The annual maintenance cost of investing in a sprinkler system is $65–$135[48] ($65 is used in the analysis). The life length of sprinkler system is taken to be 25 years. Since the experimental usage of sprinkler systems in Pakistan have led to increase in yields of up to 125 percent[49], a proportionate increase in yield is calculated for the study area with an investment in a sprinkler system. The profit for a 125 percent increase in yield is calculated by the same formula used for canal lining (see section 1.1.1). It is also assumed that during the initial year, the farmer only incurs the investment cost and from the second year he starts to spend on maintenance. In the instance where the government is providing a subsidy, the farmer should expect a NPV of $459.15 which is $219.91 more than the baseline NPV of $239.24 and therefore a very lucrative investment. However, if a subsidy is not in place and the farmer has to incur the entire investment cost of $581.81 per acre, he would experience a loss of $16.87 at the end of the 25 year period. Therefore, investment in a sprinkler system does pay off due to much higher yields but is worth investing in only if a generous subsidy or financial assistance is available to the farmer.

4.3.2 Real Options Analysis of Investing in a Sprinkler System

Real Options is the study of decision making under uncertainty. This section studies investment decisions made at two discrete points in time to show how the irreversibility of an investment decision impacts the decision to invest. This section uses the illustrative method adopted by Dixit and Pindyck (1994) to show how the irreversibility of a decision made in one period creates an opportunity cost of investing when the future value of the project is uncertain, and how this cost can be accounted for in making the investment decision, through a real life example[50].

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[48] Scherer, T (2010) Selecting a Sprinkler Irrigation System. North Dakota State University, Extension Service. Fargo, North Dakota.
[49] Alam et. al., op.cit., p. 90.
[50] Dixit, A. K., & Pindyck, R. S., (1994) Investment Under Uncertainty. Princeton University Press: Princeton, New Jersey.

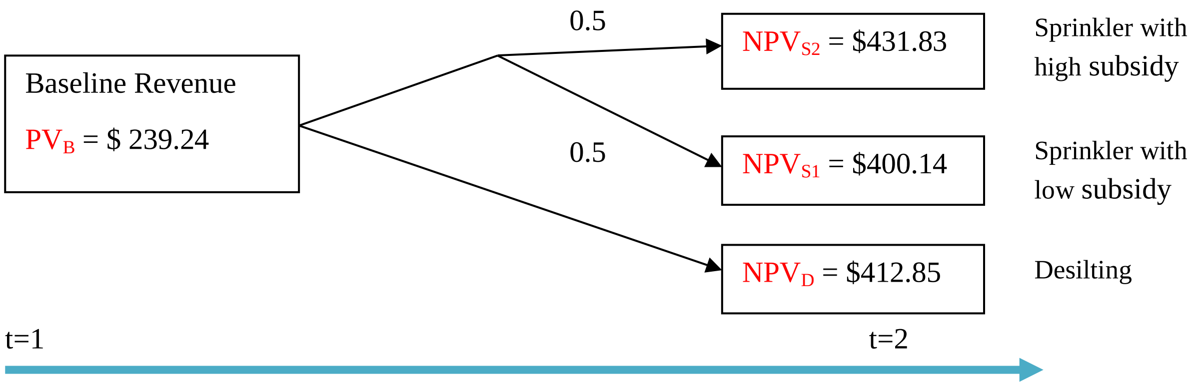

Figure 2: Real Options Analysis: Sprinkler Example

Prior to 2010, the government had offered a much lower subsidy where the farmer was paying a fixed share of $104.74 per acre (as compared to $58.19 per acre in 2010), while the government covered the rest of the investment cost. To demonstrate a farmer's decision to invest facing uncertainty about the size of the subsidy the government is going to provide in a given year, an uncertainty analysis is carried out using real options analysis. The farmer's decision to invest is studied in a two-period model where in period 1 the farmer is faced with a smaller subsidy and there is a 50 percent chance that the government will increase the subsidy. Given that the government may or may not increase the subsidy, in period 1, the farmer is faced with a decision to either invest into a sprinkler system or to desilt. At the same time, he is also flexible to wait till period 2 to invest in a sprinkler system, i.e. he has the opportunity to find out what the level of the subsidy will be and then to invest only if the higher subsidy materializes. The costs of waiting are the profits forgone from not having the sprinkler system in the first period. Real Options Analysis compares these costs to the benefits from being able to make a better informed decision at a later point in time.

The farmer's decision in each period is contingent upon his expected profits from investing either in desilting or a sprinkler system. The initial cost of desilting is $3.57 per acre and the subsidized cost of investing in a sprinkler system in period one is $104.74 per acre whereas in period two it might get reduced to $58.19 per acre. If the farmer waits to get information about the subsidy being provided in period two before he invests in the sprinkler system, he allows himself the flexibility to not make the investment if the subsidy is not introduced. With reference to Figure (2), the farmer is faced with two options: (1) to invest in desilting where his net revenue stream will be NPV_D = $412.85 and (2) to invest in a sprinkler system where there is a 50 percent chance that the lower subsidy is granted and the NPV equals NPV_{S1} = $400.14. In 50 percent of the cases, the subsidy will be higher and he will earn NPV_{S2} = $431.83. In period one, between investing in desilting and a sprinkler system, the more lucrative choice is the sprinkler system because the expected profits would be $415.99

$\left(0.5\ (\mathrm{NPV}_{S1} + \mathrm{NPV}_{S2})\right)$ compared with the NPV_{D} = \$412.85[51]. A farmer's expected profits for period one is given by the following equation:

Period 1: Expected net revenues without flexibility = $0.5\ (\mathrm{NPV}_{S1} + \mathrm{NPV}_{S2})$ **= \$415.99**

Note that despite the higher expected profits, the farmer will end up with lower profits than with desilting with a probability of 50 percent. In period two when he has more information about the subsidy which is increased by the government, the decision is reduced to a choice between sprinkler in 50 percent of the cases (namely where the subsidy is higher) and desilting in the other 50 percent of the cases, so the expected net revenues in period two for the farmer is given by:

Period 2: Expected net revenues with flexibility = $\mathbf{0.5}(\boldsymbol{NPV_D}) + \mathbf{0.5}\ (\boldsymbol{NPV_{S2}}) = \$\mathbf{422.34}$

The value of waiting (also referred to as value of flexibility or option value) for the farmer is the difference between the expected net revenues with flexibility (i.e. investment can be postponed to period 2 to make a better informed decision) and the expected net revenues without flexibility (i.e. where the farmer cannot wait for more information) which is equal to \$6.35/acre. This means that the farmer would be better off waiting till period two to invest in a sprinkler system only in the case where the subsidy is higher.

4.4 On-farm Water Storage

The investment into on-farm water storage is complicated because there are several different types of reservoirs that the farmers can invest in, with varying investment costs and life lengths. But for the sake of making the analysis simple, we have only studied the investment costs for a reservoir that is excavated and lined to allow gravity flow from canals to being stored to augment water supply. The initial cost of such a reservoir is \$653.25[52] but there is a subsidy in place like in the case of the sprinkler system, which allows the farmer to pay only a fraction of the investment cost; \$57.91 while the government pays the rest of the investment amount of \$595.34. The reservoir is usually shared amongst a group of farmers and the total cost would be divided amongst all shareholders depending on how they agree to split the cost, but for the sake of simplicity, in this analysis it is assumed that a single (representative) farmer is investing. The life length of a reservoir is assumed to be 25 years with a polyethylene (PE) lining, because if it is installed properly, it does not require periodic maintenance.

[51] Note that acting is optimal in any case, as the resulting expected NPVs always exceed PVB.

[52] PARC, op.cit., p. 36

PE lining costs much less than the polypropylene and geo-synthetic liners and lasts for at least 15 years without giving way to seepage[53].

4.4.1 Methodology

The methodology used to evaluate the viability of investing in an on-farm water storage is the net present values (NPV) of the revenue stream for 25 years, which was calculated for two instances; (1) the government is providing a subsidy and the farmer is only paying \$57.91 per acre with negligible operational and maintenance costs as they will be split amongst farmers sharing the reservoir, and (2) where the farmer is making the initial investment and paying the entire sum of \$595.34. The life length of the reservoir is taken to be 25 years. The expected increase in yield depends on whether the storage reservoir is used in conjunction with a sprinkler irrigation system where the expected increase in yield may be as high as a 100 percent or with the conventional flood irrigation system where up to a six percent increase is observed[54]. The profit for a six percent or 100 percent increase in yield is calculated by the same formula as used for canal lining (see section 1.1.1). In this case only the initial investment cost is considered and since maintenance is negligible, it is ignored for the 25 year period.

4.4.2 On-Farm Water Storage in conjunction with a Sprinkler System

In the case of using the reservoir in conjunction with a sprinkler system, and for the case where the government is providing a subsidy, the farmer should expect an NPV of \$990.32 which is \$751.08 higher than the baseline NPV of \$239.24 and therefore a very lucrative investment even if minimal routine maintenance expenses are incurred. Moreover, if a subsidy is not in place and the farmer has to incur the entire investment cost of \$595.34 per acre, he would still get a net return of \$501.74 at the end of the 25 year period. Therefore, investment in an on-farm water storage system, in conjunction with a sprinkler system, does pay off due to very high expected yields and is worth investing in even without a generous subsidy from the government.

4.4.3 On-Farm Water Storage in conjunction with Flood Irrigation

In the instance where the farmer is using the reservoir to fill the gaps for the conventional flood irrigation, the net expected profit with a subsidy is \$308.27, which is \$69.03 higher than the baseline. However, in case of no subsidy, the farmer would incur a loss of \$180.30, as the expected yields are not high enough to cover the high costs of investment. Therefore, sprinkler systems used in conjunction with surface irrigation

[53] Thandaveswara, B. S. (2011) *Lining the Canals*. Indian Institute of Technology Madras. Course Material for Hydraulics, Civil Engineering. Retrieved from: http://nptel.iitm.ac.in/courses/IIT-MADRAS/Hydraulics/pdfs/Unit22/22_1.pdf

[54] Choudhry et. al., op.cit., p. 45.

systems need to be subsidized by the government in order to be profitable in the long-run.

4.5 Comparison of Options

The investment costs per acre for each option and where a subsidy is in place are enumerated in Table 1. For each option, the net present values of the revenue streams for 25 years are also illustrated for comparison. The investment costs of extensive lining are very high compared with major desilting and profits are contingent upon the flow of canal water being above the design level at the head reaches. There is no real evidence in the literature that canal lining helps in water savings. Studies do show that more equity and canal performance issues occur at the head reaches of a canal and that is where operational improvements are recommended, however the jury is still out on whether lining is effective if performed only at the upper sections of a canal or the entire length of the canal as there is a still a great need for data collection and research in this area. Canal lining however, does provide an effective datum for maintenance activities by establishing the correct cross-section of the canals which is much more difficult in unlined canals. Van der Velde and Murray-Rust (1993) suggest that before rushing into any intervention, a clear understanding of the canal performance is required based on which effective management strategies need to be adopted. Canal operations greatly influence canal performance in a lined or unlined canal.

	Extensive Lining	**Major Desilting**	**Sprinkler Irrigation (wheat)**	**Water Storage**
Cost ($/acre)	61.02	3.57	523.68 With subsidy 58.19	595.34 With subsidy 57.91
Life Length (years)	5	5	25	25
O&M cost ($/acre)	2.02	0.95	65	0–10 percent
Increase in yield (percent)	undefined	14	103 -125	6–100
NPVs of Net Revenues ($) **Baseline NPV = 239.23**	244.14 (12 percent ↑ Y, p = 0.6)	456.07 (farmer invests) 472.46 (government invests)	459.15 Without subsidy (16.87)	*With Flood Irrigation* 308.27 Without subsidy (180.3) *With Sprinkler System:* 990.32 Without subsidy 501.74

Table 1: Investment Costs and Net Present Values of Each Option Compared

Desilting in comparison with lining has much lower initial costs and more significant benefits in terms of equitable water delivery at the tail-end[55] and the long-term revenues of tail-end farmers. The profits from investing in desilting are guaranteed whether the government makes the initial investment or the farmer incurs the initial cost, and whether major or selective desilting is performed.

Sprinkler irrigation has very high investment costs, which are paid off by very high yields and revenues in the long run and also provides the farmer with the flexibility of moving away from monoculture. However, investment is only possible if the government provides high subsidies to the farmer otherwise the farmer may face huge losses.

Investment in an on-farm water storage system is expensive but has numerous benefits such as increase in yields and revenues whether used in conjunction with flood or sprinkler irrigation system. One system can benefit more than one farmer provided that the government subsidizes the initial investment and the farmers using the reservoir share the operational and maintenance costs.

[55] Murray-Rust & Van der Velde (1993), op.cit. p. 85.

5 Discussion & Conclusion

The aim of this study has been to explore a number of options to improve the economic conditions of the tail-end farmers, and to make use of the available water in the most efficient way possible. This study is a step towards helping the tail-end farmers to understand how far they can improve their conditions by investing in alternative solutions on their own assuming that farmers have the necessary knowledge, market access and liberty to grow what they want. It also assists the policy makers in deciding which projects to subsidize and what policies to put in place to help the tail-end farmers in the long-run.

It is recommended to the farmers that some interventions, such as canal desilting, are affordable and can be implemented on immediate bases to significantly improve the canals' hydraulic conditions and to bring the channel to flow up to the design levels so that in the short run, the farmers can get their promised seasonal water allocations. This intervention can be initiated through the farmer organizations and, where required, complemented with canal lining to maintain the canal cross-sections.

To further improve the yields and productivity of the tail-end farmers, the study suggests investing in new irrigation technologies particularly sprinkler irrigation system and if possible complementing with an on farm storage system to further augment the water supply and allow flexibility in the timing of irrigation. The study shows that these interventions lead to significantly high future yields and revenue streams. However, for that to occur, substantial financial support from the government is critical, without which the investment is too risky, especially in sprinkler irrigation and on-farm water storage systems.

In the long run, improvements in the systemic level are possible and for that the policy makers are recommended to make some adjustments in the management structure of the canal system. The irrigation management transfer has been a success story. Not only has it empowered the farmer by creating farmer organizations but has also reportedly reduced water theft incidents in the secondary canals (see Appendix C). Similar interventions and structural changes can allow water markets to exist and streamline the informal trading practiced amongst the farmers in Pakistan. With an existing government body, such as the area water boards overseeing transactions and acting like a clearing house, the equilibrium price determined by the market can become optimal. Information about water suppliers can be made common knowledge by the authorities and the transaction costs can be minimized.

Further improvement in farmer revenues can be obtained through crop diversification and where risks are high for the farmers, the government should intervene by providing subsidized input resources such as capital for more capital intensive crops and other agriculture extension services and information to allow farmers to make more informed decisions when choosing a crop portfolio.

Further research can explore these options in more detail when more data is collected. The option of water trading can be expanded to include groundwater markets and trading between districts and watersheds. The crop portfolios can be analyzed better by collecting the cost data for each crop type and subtracting it from the prices to determine their respective profits before calculating an optimal crop portfolio. Also, more information is required on how farmers use their land holding currently in order to make more precise recommendations.

Future work can also delve into various new directions, such as, looking at the possibility of diverting tail-end farms to non-irrigation agricultural uses and allowing more canal water to be used by the head and middle farmers. It should also entail comparisons of water productivity within the Indus Basin Irrigating System (IBIS) with that of other regions using similar irrigation techniques to identify the factors behind low water productivity in the IBIS. Furthermore, future research work can be extended to include hydrological studies at the macro level such as the impact of systemic changes on the river basin, particularly the impact on groundwater recharge, river flows, evaporation and availability of water in the basin as a whole. The use of hydrological modeling to look at the water balance of the Indus River basin, by using surface, subsurface and water quality and climate data would be very useful.

Appendix

A Benefits of Crop Diversification

Wheat is one of the cash crops for the *rabi*[56] season in Pakistan. The farmers for which the data has been collected, are growing wheat as their primary source of income. Moving towards more efficient irrigation technologies can provide the farmer with the flexibility of moving away from monoculture and growing a variety of crops in a given season. This section explores the option of growing crops in addition to wheat to allow for risk hedging against crop price volatility, and other interventions affecting farmer revenues. Expected prices and the associated covariance matrix were calculated to determine the crop portfolio that minimizes risk given a minimum required profit or maximizes profits given a maximum allowed level of risk. The crops selected for this analysis are wheat, pulses[57], lentils[58] and maize as these are the most commonly cultivated crops in the area for the *rabi* season.

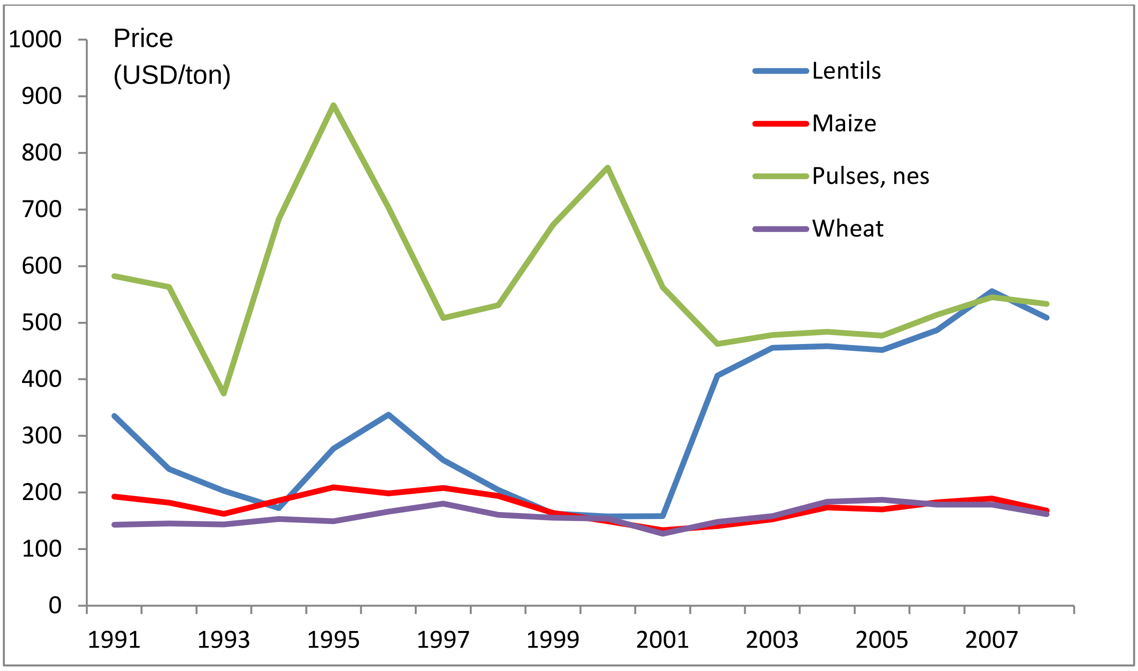

Figure 3: Producer prices for selected crops[59]

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[56] There are two cropping seasons in Pakistan; Rabi (winter) and Kharif (summer).

[57] Pulses are leguminous crops yielding from one to twelve grains or seeds of variable size, shape and color.

[58] Lentils are is an edible pulse, grown for its lens-shaped seeds that grow in pods, usually with two seeds in each.

[59] The graph in Figure 3 is generated from time series data retrieved from FAO STAT database.

The producer prices per ton for each crop over two decades are retrieved from FAO STAT to generate the graph given in Figure 3. This graph shows that for the past twenty years, the prices of wheat and maize have remained constant with very little variability, while those of lentils and pulses have fluctuated considerably during the mid-90s but have stabilized after 2002. The constant wheat prices are due to price control by the government or setting of wheat quotas which fixes a certain wheat output for a given area or region [60]. To measure the volatility of the crop prices and the effect of this volatility on the expected returns, the data is used to calculate a covariance matrix of the profits from producing one ton of a given crop.

Methodology

The calculations in this section assume input costs to be the same across all crops although the preparation and harvesting/processing of lentils and pulses is relatively more labor and capital intensive than that of wheat. Therefore, only prices per ton of each crop are used to derive the results of this analysis. The expected profit level may be slightly lower in reality, but not so low that it would impact the composition of the optimal portfolio. In order to calculate the portfolio variance for each of these crops, the changes in prices were calculated for each year. Then a regression was performed saving the residuals. These residuals were used to calculate the covariance-variance-matrix, providing information for the minimization of the portfolio variance, σ_P^2, subject to a minimum required expected portfolio profit $\tilde{\pi}_P$ using the following formula:

$$\min_{X_i} \sigma_P^2 = \sum_{i=1}^{N} \sum_{j=1}^{N} X_i \cdot X_j \cdot \sigma_{ij}$$

$$s.t.\ E[\pi_P] = \sum_i X_i \cdot E[\pi_i] \geq \tilde{\pi}_P$$

where X_i is the weight of crop *i* in the portfolio. The variance of crop prices is used here to measure the variability of a farmer's profit from crop diversification[61].

	Lentils	Maize	Pulses	Wheat
Lentils	9525.542714	885.887953	-2838.89489	488.2940712
Maize	885.8879532	430.444231	548.0120858	201.027232
Pulses	-2838.89489	548.012086	14257.08545	-107.058166
Wheat	488.2940712	201.027232	-107.058166	192.3135555

Table 2: Covariance matrix of the crops in US$/ton

[60] Dorosh, P., Salam, A. (2006) Wheat Markets and Price Stabilization in Pakistan: An Analysis of Policy Options. Pakistan Institute of Development Economics. PIDE Working Papers 2006:5.

[61] Ross, S. A., Westerfield, R. W., Jaffe, J. (1999) Return and Risk: The Capital-Asset-Pricing Model (CAPM). In *Corporate Finance, 5th Edition*. USA: Irwin McGraw-Hill.

Using the variance as the risk measure and the expected profits, we minimize the risk subject to a minimum constraint on expected profits.[62] In this way, the optimal crop portfolio is determined for different minimum levels of expected revenue[63], as shown below.

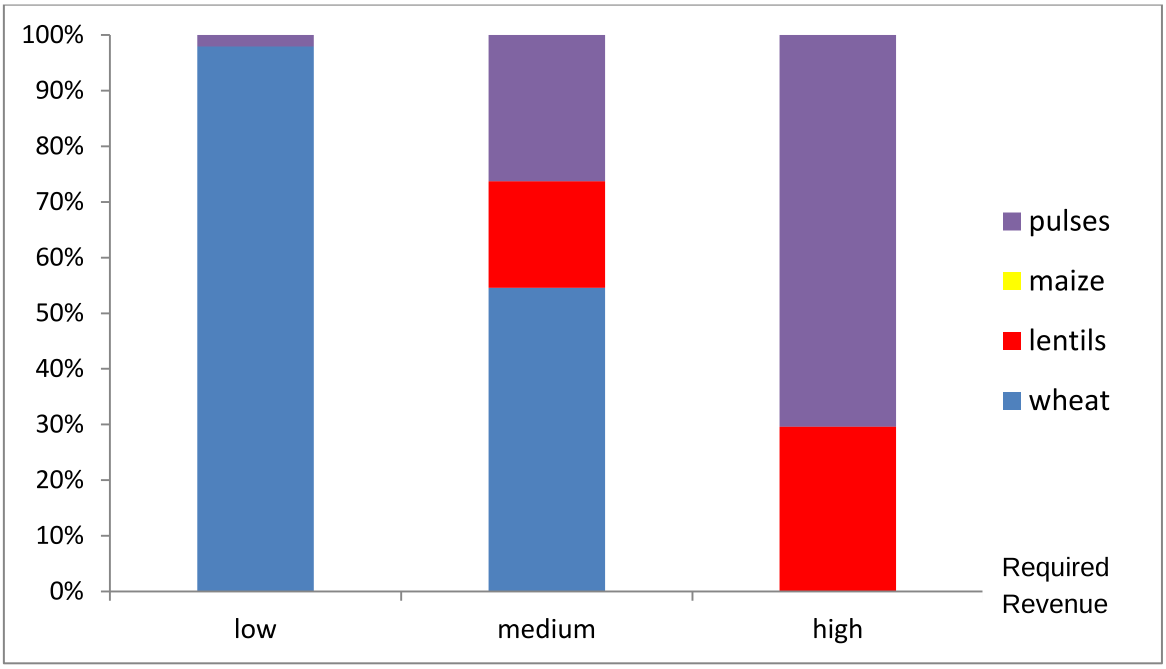

Figure 4: Crop Portfolio

Figure 4 illustrates that the farmer should grow a mix of wheat and pulses with significantly more wheat than pulses if he wishes to lower his risk and in turn accept lower profits. However, if he wishes to increase his profits he should grow a mix of pulses and lentils but at a much higher risk originating from the higher price volatility of these crops.

Caveats

Although crop diversification allows for risk hedging against crop price volatility and other factors affecting farmer revenues and provides many benefits to the farmer from growing a variety of crops if an alternate irrigation system is in place, there are certain caveats to this analysis. First of all the data set of the farm input data, used in this study, only looks at wheat yields of the farmers and does not record the yields or cultivation of other crops on their farm holdings. Secondly, the farmers may be focusing on wheat due

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[62] Similarly, one can maximize expected profits subject to a maximum constraint on risk (variance) that is considered to be acceptable.

[63] Analogous to a portfolio consisting of financial assets, requiring a higher minimum return will imply that the investor has to accept a higher level of risk as well.

to lack of market indicators and other information that is not readily available to the farmers to allow them to fully benefit from crop diversification. The third caveat is that there are informal institutions existing in the rural society, like feudalism, that dictate how tenant farmers should pay their land lords. At times this payment is made in-kind, like bags of wheat rather than cash, which can influence what a tenant farmer grows on his rented land. Furthermore, what the analysis is missing is the comparison of yields from each type of crop obtained from a given measure of land. From a recent interview of a farmer, the lead author discovered that although lentils and pulses may be priced much higher than wheat in the market, the yields of lentils are less than half that of wheat in a given season and require longer labor hours in the field – contrary to common wisdom - which is why farmers prefer wheat over other crops. Therefore, more data needs to be collected on the input costs for each crop so that the profits per ton of growing each crop can be used to calculate the optimal portfolio.

Even though the analysis is rather simple, it serves its purpose of demonstrating the merits of diversification, the opportunity that is opened up by improved irrigation practices such as installing a sprinkler system. The results in the context of the caveats also point to another conclusion, namely that if small tail-end farmers are part of a feudal system and without access to markets, then welfare gains are still possible by passing the recommendation to shift away from monocultures to landlords.

B Improved Timing of Water Delivery through Water Trading and Markets

Water is a crucial input for agricultural productivity but its insufficient and untimely delivery limits the farmers' use of other inputs, resulting in lower yields. Currently the farmers are paying an annual water tax of $1.56 per acre regardless of how much water they obtain from the canal and what they decide to grow on their land. The farmers are also faced with a much higher price of $13.90 per acre for extracting groundwater which is of much lower quality than the canal water. According to the data, on average each farmer irrigates his land with four complete irrigations in a season, where one irrigation unit consists of approximately three acre-inches of water[64]. The cost of one additional irrigation unit depends on whether the water is extracted from the canal or the ground. To allow for trading of canal water within the irrigation system, so that good quality water can be distributed more equitably and more productively across the channel, a market-based system with a focus on an appropriate water pricing system is the solution explored in this section as an option to cope with water shortages and high water costs at the tail-end of the canal.

Informal Canal and Groundwater Trading in Pakistan

Pakistan's irrigation system is a gravity flow system, designed in a way to provide water to as many users and to cover as much area as possible. The water supply is not organized according to the crop water requirements but is rather designed for deficit irrigation that assumes a low cropping intensity[65] of about 60–80 percent to make irrigation reasonably productive. With time, more and more arable land has been added to the irrigation system, so the cropping intensities have increased up to 150 percent, rendering the supply of canal water inadequate[66]. The water is channeled from the rivers by barrages onto the main canals where the water is supplied continuously up until it reaches the outlets of the watercourses (tertiary level). From here onwards the water is supplied in a method called *Warabandi.*[67] Warabandi is a rotational method of equitable allocation of water where water turns are fixed according to a time roster, specifying a day, time and duration of supply to each irrigator. The warabandi provides a continuous flow of water for flood irrigation in which one complete cycle of rotation generally lasts

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[64] Sahibzada, S. A., (2002) Pricing Irrigation water in Pakistan: An Evaluation of Available Options. *The Pakistan Development Review,* 41:3, pp. 209–241.

[65] Cropping Intensity = (Total Cropped Area / Total Cultivated Area)

[66] Latif, op.cit., p. 510.

[67] Bandaragoda, D. J. (1998) *Design and practice of water allocation rules: Lessons from warabandi in Pakistan's Punjab*. Research Report 17. Colombo, Sri Lanka: International Irrigation Management Institute. p. 2.

seven days. The duration of supply for each farmer is proportional to the size of the farmer's landholding to be irrigated within the particular watercourse command area.[68]

In response to the rigid allocation scheme and the unreliability of actual water deliveries compounded by silting and illegal breaching of canals[69], farmers have developed an informal system of water trading such as rotation of turns where farmers alternate their water turns to improve equity. Water turns are clumped together and used jointly by two or three farmers – this happens usually when all three belong to the same family. Substitution of turns is common when the landholding is small and the time share is short. The farmer gives his turn to a nearby large landowner and after two or three turns the large landowner compensates with sufficient water supply to irrigate the entire plot of the small land owner. Exchange of turns or borrowing or lending of water turns is prevalent amongst farmers looking to increase the flexibility of water supply. Similarly, trading of turns or informal buying and selling of canal water turns also takes place to meet the crop requirements[70].

Groundwater markets in Pakistan have also emerged over the past few decades due to a rapid growth in private tubewells. These markets are characterized by monopoly power, barriers to entry and extreme spatial fragmentation. Barriers to entry arise because one must own land above an aquifer before boring a tube well and incur high installation costs. Seepage losses from conveying groundwater over unlined canals severely impedes competition. Since groundwater markets and tenancy are interlinked, a monopolistic tubewell owner charges a lower price (marginal cost/ extraction cost) to his own share tenants than he does to other cultivators simply because he shares their output. However, the monopoly pricing of groundwater leads to informal exchange of canal water since canal water is free at the margin whereas groundwater is expensive to extract. Farmers resort to tubewells only in times of peak water demand; instead they borrow canal water turns from tubewell owners and their tenants as during these critical periods the owners and their tenants are obtaining more groundwater than other users. This loan is paid back during periods of slack water demand when groundwater is seldom used. These canal water transactions are carried out in-kind[71]. However, personal interviews suggest otherwise. Water prices for trading allocations are determined between the trading farmers based on proximity and ease of transfer without the involvement of any intervening body, although area water boards do exist and oversee canal water tax collection and seasonal water allocations. This informal water price determination lacks a whole market analysis and so the determined price may be

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[68] ibid.

[69] Bandaragoda, D. J., Rehman, S. (1995) Warabandi in Pakistan's Canal Irrigation Systems – Widening Gap between Theory and Practice. Colombo, Sri Lanka: International Irrigation Management Institute.

[70] Bandaragoda. op.cit. pp.19

[71] Jacoby, H. G., Murgai, R., Rehman, S. U. (2001) Monopoly Power and Distribution in Fragmented Markets: The Case of Groundwater. International Water Management Institute, Lahore.

sub-optimal as farmers do not have all the information about the farmers willing to trade in the whole market.

According to Jacoby et. al. (2001) due to the presence of a parallel canal water market, more canal water is diverted to farmers facing higher monopolistic groundwater prices. In theory, the difference in crop yields between tubewell owners/ tenants and other buyers is not as large as would otherwise be if only groundwater was being traded[72].

The equilibrium price of water for the study area

To assess the impact of formal trading on trading volumes and price, the equilibrium price of water for the study area is determined in this section. The equilibrium price of water is the price at which the demand for water is satisfied by the supply and for profit-maximizing farmers an engagement in trading could be an opportunity to increase their profits. This equilibrium price is calculated by first determining the profit functions dependent on the number of canal water irrigations of the head, middle and tail-end farmers along a channel. For this purpose, average number of canal water irrigations and the corresponding average net revenues of each set of farmers are used as given in the data set, where farm level cross sectional data has been compiled based on primary and secondary data collection methods. The analysis focuses on canal water because water is the constraining factor input in this study and the canal water supply for a given season is taken to be fixed[73].

The non-linear profit function for the farmers is then derived by fitting a logarithmic function to the data points and is given by the following general equation:

$$\pi = C_0 + C_1 \ln (w - x) + x(p_c - p_g)$$

Where $\boldsymbol{w}$ is the average water supply to each farmer at a given location, $\boldsymbol{x}$ is the number of irrigations the farmer is willing to give up (if x is positive) or absorb (if x is negative), $\boldsymbol{p_c}$ is the traded price per irrigation of canal water and $\boldsymbol{p_g}$ is the fixed price for one irrigation of groundwater taken to be approximately \$13.90 per acre[74]. The groundwater price is not allowed to fluctuate in the profit function, only the cost of extracting groundwater is accounted for. C_0 is the intercept, denoting the profit made by one farmer in the hypothetical case that he gives up all his irrigation units and the price

[72] ibid.
[73] Absar, M. (2009) Choice of Farm Inputs in Response to Uncertain Irrigation Supplies in Pakistan. (Working Paper) Master's Thesis, Yale School of Forestry and Environmental Studies.
[74] The total number of irrigations for a season are 4 or 5; the irrigation deficit is covered by groundwater irrigations.

of groundwater is equal to the traded price of canal water, and C_1 is the coefficient showing the influence of the number of irrigations a farmer gets on his profits.

The three profit functions for head, middle and tail-end farmers are:

$$\pi_h = C_0 + C_1 \ln(w_h - x_h) + x_h p_c - p_g x_h$$

$$\pi_m = C_0 + C_1 \ln(w_m - x_m) + x_m p_c - p_g x_m$$

$$\pi_t = C_0 + C_1 \ln(w_t - x_t) + x_t p_c - p_g x_t$$

Where $\boldsymbol{\pi_h}$ is the profit of farmers at the head of the channel, $\boldsymbol{\pi_m}$ at the middle and the $\boldsymbol{\pi_t}$ at the tail-end and $\boldsymbol{x_h}$, $\boldsymbol{x_m}$ and $\boldsymbol{x_t}$ are the quantities of water traded at the head, middle tail-end respectively. The term $\boldsymbol{x_h p_c}$ means that the quantity of canal water traded is multiplied by the price of canal water and $\boldsymbol{p_g x_h}$ is the term subtracting the quantity of groundwater multiplies by the cost of groundwater from the equation. The log function reflects the property of decreasing marginal benefits of irrigation, i.e. one more irrigation will eventually lead to lower revenue gains than the previous one.

	Channel Head	**Channel Middle**	**Channel Tail**
Average Net Revenue (US$)	56.21	49.66	34.35
Canal Irrigations	2.54	2.023	0.50
Tubewell Irrigations	1.71	2.11	3.50
Total Irrigations	4.25	4.14	4.00

Table 3: Average net revenue and average number of irrigations ($/acre/season) for each location.

Using the average canal irrigations from Table 3 for $\boldsymbol{w}$ or the average water supplied to farmers in their respective locations, and using the values of *2501.3* and *1714.6* from the logarithmic function for $\boldsymbol{C_0}$ and $\boldsymbol{C_1}$ respectively, where C0 is the intercept, i.e. if the logarithmic term equals zero, then the farmer will earn c0 and the market price of water multiplied by the amount of water sold, and US$13.90 for $\boldsymbol{p_g}$, the price of water is determined at which water is traded to maximize profits for each location respectively.

For a given channel to be in equilibrium, the negative sum of water given up by the head and middle end farmers should be equal to the total amount of water received by the tail-end farmers or that the sum of all traded quantities must equal zero. The price inherent at the point of the intersection of equilibrium supply $(x_h + x_m)$ with equilibrium demand (x_t) gives us the equilibrium price of trading water across the channel for farmers willing to trade in order to maximize profits.

p_c (US$)	x_h	x_m	$Supply = (x_h + x_m)$	$Demand = x_t$
25.50	0.9	0.3	1.2	1.2

Table 4: Quantities of water demanded and supplied at equilibrium

At a price of US$ 25.50, the demand for irrigation water equals the supply. At this price, the head farmers would sell 0.9 irrigations, while the middle end farmers would trade 0.3, combined, these would equal the irrigations demanded by the tail-end farmers. The equilibrium price of canal water is substantially higher than the price for groundwater which captures the fact that canal water is of better quality and significantly influences the farmers' profits. This example illustrates that everyone is gaining from trade and there are increases in total welfare from higher profits i.e. it is a *Pareto* improvement. As expected, the tail-end farmers are gaining the most. The equilibrium price of canal water is almost twice that which farmers are willing to pay for groundwater (US$13.90) which makes trading canal water far more lucrative and also gives an incentive to the farmers to use the canal water in a more efficient manner.

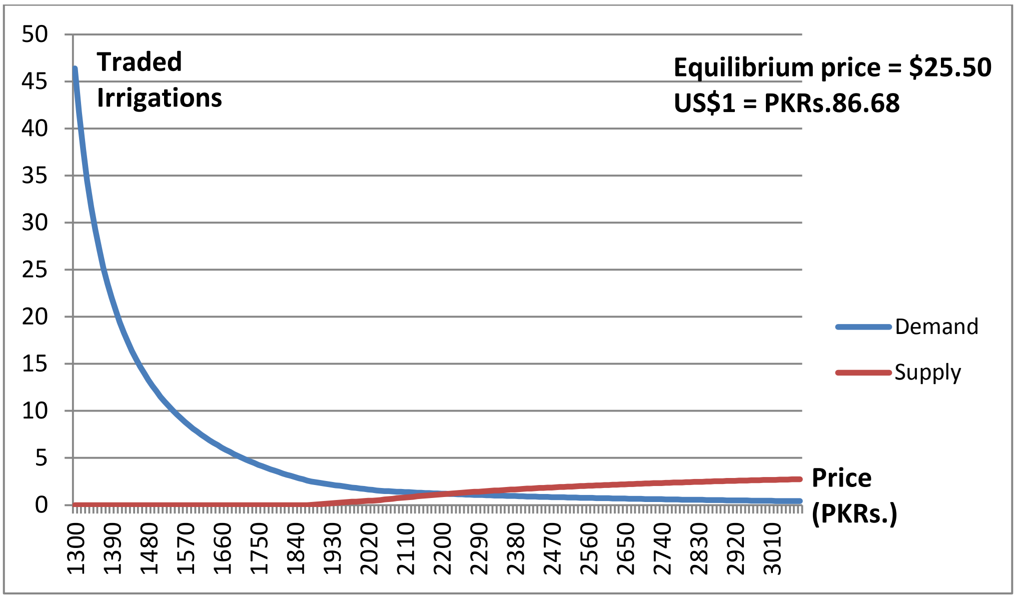

Figure 5: Equilibrium price for trading water to maximize profits

At the equilibrium price, the profits for each location and the sum of net revenue across the channel are given in Table 5.

US ($)	π_h	π_m	π_t	Total π
With trading	49.14	43.20	25.37	117.71
Without trading	47.30	42.86	15.15	105.30

Table 5: Net revenues with and without trading of canal water

The market if left to determine the price of water would determine a price that would allow the farmers to maximize their profits and make more efficient use of water.

Equating Profits across all reaches of the Channel

To illustrate the case in which the government equitably distributes the water amongst the farmers such that all farmers get the same net revenue. We have equated the profits of all farmers across head, middle and tail sections to see what equal distribution of water would look like in terms of the net revenues.

Price (US$)	x_h	x_m	x_t	π_h	π_m	π_t	Total π
0	0.4	0.18	-0.58	38.37	38.53	38.41	115.31

Table 6: Quantities traded to equate profits across all farmers.

At a price equal to zero, the net revenues at head, middle and tail are the same at US$38. The sum of all profits is equal to US$115.31, which is less than the sum of profits when the water market is in equilibrium but still this is higher than the profit currently earned by the farmers when no formal water trading is taking place (see Table 5). This shows that even under a centralist system, the farmers will be much better off.

The above empirical and economic analysis shows that there is vast potential for water markets in Punjab, Pakistan. Water trading in Pakistan can be carried out through formal markets overseen by water utilities or the exiting Area Water Boards (AWBs) that are responsible for providing seasonal water allocations and collecting annual water tax. Currently the AWBs are financially self-sufficient entities at the canal command levels with functions similar to a utility company. They are also responsible for the irrigation and drainage management of the main canal system, including bulk water supplies to the head of the distributaries.[75] Their mandate can be modified to incorporate collecting appropriate data in the water market and administration of canal water trading amongst farmers based on their water entitlements and seasonal allocations and to serve as a clearing house between trading farmers. The AWBs can also provide information about water supply and pricing to the Farmer Organizations to make the process more streamlined and effective.

[75] Punjab Irrigation and Drainage Authority (2011) General Social and Economic Condition of Area Water Boards. Retrieved from: http://pida.punjab.gov.pk

C Water Theft Reduction through Devolution of Power

The Punjab Irrigation and Drainage Authority (PIDA) has planned to create a multi-tiered system for transfer and decentralization of management and community participation as part of the irrigation institutional reform program of the Provincial Irrigation Department (PID). The multiple tiers include PIDA, Area Water Board (AWB), farmer organization (FO) and the farmers. The FO is an elected body of farmers that represents farmers at the minor/ distributaries level and forms an interface between the farmers and all the upper tiers. The functions of FOs include operation and management of the irrigation and drainage infrastructure, equitable distribution of water in their designated areas of representation and collection of *abiana* from the farmers. A percentage of the dues collected is kept by the FOs to cover their operational costs[76].

The Irrigation Management Transfer (IMT) is an institutional policy reform proposed by the World Bank and initiated by the government of Pakistan in the early 1990s. This reform model was formalized under the PIDA Acts in 1997 and officially implemented in April, 2000. Under this model a three-tier irrigation structure and drainage management system was devised with PIDs responsible for province-wide water distribution, system maintenance and development, and sales of water beyond amounts contracted with the AWBs. As the operating public utility, the AWBs were to provide bulk water to the FOs, through formal volume based contracts. An AWB roughly covered an area of a million hectares and also traded water with other utilities. The FOs supply water to the irrigators and are responsible for the operation and maintenance of secondary irrigation canals and to levy and collect water charges to be paid to the AWBs. In practice, the reforms ensure greater farmer representation in the system management although the contractual arrangements between the FOs and AWBs are one-sided and top down, where the FOs are accountable to the AWBs and the PIDs. The PIDs retain the power to cancel any contracts between the FOs and the AWBs and declare some canal commands exempted from water payments[77].

The implementation of the IMT has had some positive impacts on the irrigation system. Equity in water distribution in a shared system means that a proportionate and fair share of irrigation water is provided to all stakeholders regardless of their location along a distributary. In the current irrigation system some outlets are drawing more than their authorized share at the cost of the fair share of some other outlets in the system. In the pre-transfer period the outlets were drawing 5–65 percent more water than their due share and there was a very high variation in water supply to the outlets. This means that

[76] Punjab Irrigation and Drainage Authority (2007) Scheme for Transfer of Irrigation Management – Farmers Organizations in Punjab.

[77] Hassan, M. U. (2009) The Conception, Design and Implementation of IMT in Pakistan's Punjab: A Public Policy Reflection. SAWAS, 1 (2): 132–142.

the pre-transfer period saw highly inequitable distribution of water. There was poor management and outlets (feeding the watercourses) were tampered with. Immediately after the management transfer to the farmers, a gradual improvement in equity was observed. Also, there was a marked improvement in the variability of supplies to the outlets as compared to the corresponding pre-transfer period. Latif and Pomee (2003) attribute this improvement to patrolling, correction of faulty outlets, absence of theft incidents, regular desiltation of the canals and proper repair and maintenance of the control points under the FO management. Before the IMT took place in 2000, water theft incidents were very common. The FOs put in extra efforts to remove the water theft incidents from the upper lined reaches of the tributaries but they had no power beyond the canal head regulator and could only intervene below this point at the secondary and tertiary canal levels[78].

[78] Latif, M., & Pomee, M. S. (2003) Impacts of institutional reforms on irrigated agriculture in Pakistan. *Irrigation and Drainage Systems **17***, 195–212, p. 201.

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