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IRRIGATION INVESTMENT BRIEFS

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by

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(**Editor's note:** Regrettably some tables and figures and a 14th paper on the "Pumping Cost of Irrigation Water" that appeared in the original printed version could not be reproduced in this PDF edition of the document.)

IRRIGATION INVESTMENT BRIEFS

FOREWORD

Investments in irrigation can contribute importantly to increased agricultural production and economic benefits if planned, implemented and operated satisfactorily. The range of options available for investments is generally wide and careful selection on technical and socio-economic grounds is required to ensure optimum returns from the investments on a sustainable basis.

The following papers have been written over the past eight years in the course of providing assistance to developing countries in the preparation of World Bank-financed irrigation projects in various parts of the world. They cover topics which have arisen in the course of field work, including technical and economic issues discussed in the field and requiring clarification, and also record experiences on actual case situations. The papers have been issued individually and distributed to the project staff concerned. However, as much of the material is of wider interest, they are now being issued collectively for more general distribution.

It must be emphasized that the papers do not aim to provide a systematic treatment of the subject of investment in irrigation (and drainage), although most of the key factors to be considered for investment are discussed. The papers may, however, provide, a useful source of reference for those engaged in this area.

The papers have been reproduced in the original (unedited) form.

The contribution and assistance of colleagues in preparation of the series is gratefully acknowledged.

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IRRIGATION INVESTMENT BRIEFS

CONTENTS

1. DETERMINING IRRIGATION DEVELOPMENT OPTIONS (September 1989)
(A Case Study)

Introduction

1. Irrigation developments usually have multiple aims. Some of the most frequent are to reduce dependency on agricultural imports, to generate exports, to reduce fluctuations in output, to intensify production, to aid human survival in semi-arid areas in times of drought, to raise farmer incomes, to create employment, to keep parastatal or private contractors in work, or to raise political monuments. But all irrigation thing in common: they use scarce resources, whether these be natural (water, irrigable land), managerial, or financial. Furthermore much of the financial contribution of governments in the case of existing irrigation tends to be borrowed, hence must eventually be repaid.

2. Whatever the mix of economic and social aims to which a government gives ultimate priority in its irrigation strategy, it is therefore prudent when planning sub-sectoral development to estimate the economic efficiency of the use of the natural and financial resources which will be used. With such estimates, comparison can be made between irrigation alternatives, and with rainfed options if these exist. If at national level it is decided for social reasons to favour one of the less economically efficient forms of irrigation, the extra public cost of doing so can be identified. From the point of view of the national finance ministry or a potential lender, the justification for, and the economic implications of the overall programme which is eventually proposed for financing are made explicit. If changes or adjustments are considered necessary they can be negotiated on a rational and quantified basis.

3. In practice, few irrigation developments are based on such estimates as most irrigation planners do not have technical expertise to make a systematic review of the economic efficiency of all technical options when formulating a national irrigation strategy. This paper describes therefore, as an example, the methodology used to derive at such a strategy for the case of Malawi[1].

The Irrigation Setting

4. The Government's objective was to expand irrigation from presently about 22,000 ha to 42,000 ha through implementation of a single 20,000 ha project. Even though land and water resources were plentiful for the proposed project it was in sharp contrast to the past small-scale public irrigation development. Furthermore, the physical infrastructure needed appeared fairly capital intensive and the managerial capacity of the irrigation agency

[1] For a different case ref. also to "Estimating the Economic Efficiency of Irrigation in the Case of Brazil", FAO/CP Working Paper, 1989/3.

to handle such a relative large scheme (being 50 times larger than the biggest in existence) insufficient. Since the irrigation potential of Malawi is more than 100,000 ha and spread throughout the country, investigations were made therefore as to what other options were available and at what cost. In addition, the limited managerial capacity needed to be considered for implementation and operation of the options. The outcome of the investigations had to be presented in such a way as to allow comparison among options and the proposed project of 20,000 ha.

Technical Options and Their Cost

5. During the course of the investigations, 12 additional options for development were identified. Their type, cost (in Malawi Kwatcha; US$1 = MK2.8), implementation and operational ease are shown below in Table 1 together with the data for the proposed 20,000 ha project. The total annual cost for the individual options in Table 1 column 3 where estimated in Table 2 for the gravity schemes and in Tables 3 and 4 for the pumping schemes. The annual recurrent cost to Government (column 4) (an important consideration if Government funds are limited) were estimated or taken from local experiences where possible. Information on implementation and operationable ease (columns 5 and 6) was derived from local and foreign experiences.

Table 1. Options for Irrigation Development with Costs and Their Expected Implementation and Operational Ease

Option	Irrigated Area	Capital Investment	Total Annual Cost [a]	Annual [b] Recurrent Cost to Government	Implementation [c]	Operation [c]
	ha	……(MK/ha)……				
	1	2	3	4	5	6
GRAVITY SCHEMES						
Self-help scheme*	5-10	800	168	80	3	2
Reservoir self-help scheme	8-12	8,500	1,190	80	4	2
Government Scheme *	200-400	14,000	2,040	500	5	5
Proposed Project	20,000	23,000	3,050	620	6	6
PUMPING SCHEMES						
From open water surfaces						
Small electric pump	1-2	1,000	80	none[d]	1	1
Low lift diesel pump	4-6	1,250	560	none	2	3
Portable petrol kerosene pump	1-2	1,600	640	none	1	3
Portable petrol/kerosene pump with sprinkler	1	2,000	2,250	none	1	3
High lift pump project	2,000	24,500	4,265	800[e]	6	6
From groundwater						
Shallow tubewell - electric pump	1-2	3,000	1,440	80[d]	4	2
Shallow tubewell - diesel pump	4	2,000	1,200	80	4	3
Shallow tubewell - petrol/kerosene pump	1-2	3,600	2,240	80	4	3
Deep tubewell* - electric pump	6-10	10,000	2,200	80[d/e]	5	2

* Existing Systems.
[a] Ref. Table 2 for details.
[b] Assuming water charges are not collected.
[c] 1 = easy, 6 = difficult.
[d] Recurrent cost of electricity production and its transmission not considered.
[e] Electricity charges borne by farmers.

US$1 = MK2.8

Table 2. Calculation and Summary of Total Annual Cost for Various Options

Option	Investment[a]	Depreciation/Year	Interest/Year	O&M per Year	Total Annual Cost
	.... MK/ha				
GRAVITY SCHEMES					
Self-help scheme	800	40	48	80	168
Reservoir self-help scheme	8,500	450	540	200	1,190
Government Scheme	14,000	700	840	500	2,040
Proposed Project	23,000	1,150	1,380	620	3,050
PUMPING SCHEMES					
From open water surfaces					
Small electric pump	1,000	.... see Table 3			80
Low lift diesel pump	1,250	.... see Table 3			560
Portable petrol/kerosene pump	1,600	.... see Table 3			640
Portable petrol/kerosene pump with sprinkler	2,000	.... see Table 3			2,250
High lift pump project	24,500	1,225	1,450	1,570	4,265
From groundwater					
Shallow tubewell - electric pump (1 ha)	3,000	.... see Table 4			1,440
Shallow tubewell - diesel pump (4 ha)	2,000	.... see Table 4			1,200
Shallow tubewell - petrol/kerosene pump (1 ha)	3,600	.... see Table 4			2,240
Deep tubewell - electric pump	10,000	1,000	600	600	2,200

[a] US$1 = MK2.8

Table 3. Cost of Pumping From Surface Water With 4 Different Technical Options

Basic Data	Electric	Diesel	Petrol/Kerosene
Price to farmers (K) including centrifugal pump unit and pipes	1,000	4,500	1,600
Power rating	2 hp	5 hp	3 hp
Power used	2 hp	4 hp	2 hp
Economic life (h)	12,000	7,000	1,500
Interest rate (%)	12	12	12
Weight (kg)	20	150	30
Energy consumption (litre/h)	1.5 kWh	1	0.6

		Electric[a/]	Diesel	petrol/Kerosene	Petrol/Kerosene with Sprinkler for 1 ha
		………………………………MK………………………………			
Fixed Cost/h					
Depreciation:					
Electric (1,5 kW)	MK1,000 / 12,000 h	0.08			
Diesel (5 hp)	MK7,500 / 7,000 h		1.07		
Petrol/keros. (3 hp)	MK1,600 / 1,500 h			1.06	MK2,000 / 1,500 = 1.33
Interest at 12%					
Electric	MK1,000 x 0.12 x 16 y / 12,000 h x 2	0.08			
Diesel	MK7,500 x 0.12 x 14 y / 7,000 x 2		0.90		
Petrol/keros.	MK1,600 x 0.12 x 3 y / 1,500 h x 2			0.19	MK2,000 x 0.12 x 2 y / 1,500 h x 2 = 0.16
Sub-total		0.16	1.97	1.25	1.49

(Editor's Note: regrettably the above Figure could not be reproduced in full in this PDF edition of the document.)

Table 4. Cost of Pumping From Groundwater With 3 Different Options

Basic Data	Electric	Diesel	Petrol/Kerosene
Price to farmers (K) including centrifugal pump unit and pipes	1,000	4,500	1,600
Power rating	2 hp	5 hp	3 hp
Power used	2 hp	4 hp	2 hp
Economic life (h)	12,000	7,000	1,500
Interest rate (%)	12	12	12
Weight (kg)	20	150	30
Energy consumption (litre/h)	1.5 kWh	1	0.6

(Editor's Note: regrettably the Figure shown below on p 6 of the printed paper could not be reproduced in this PDF edition of the document.)

Economic Benefits

6. The calculation of benefits was based on a "without irrigation" scenario of maize mono-cropping (one crop per year) and a "with irrigation" scenario of a rainy season maize crop supplemented by irrigation followed by a fully irrigated rice crop.

7. This cropping pattern had been selected despite its lower irrigation water use efficiency compared to growing rice during the rainy season and maize during the dry season in the belief that Malawi farmers would give preference to their staple maize crop during the rainy season and regard rice as a cash crop only. Maize yields were expected to increase from 1.15 t/ha to 2.5 t/ha. The net benefits of the rice crop facilitated by irrigation were fully attributed as incremental benefits to irrigation. However, based on knowledge of existing schemes and the lack of general experience with irrigation in Malawi it was considered prudent to assume only a 60% cropping intensity for the rice crop as a 20-year average. The analysis showed that the discounted benefits over a 20-year period at 12 per cent amounted to about MK9,000 (Table 5 and 6).

8. An additional incremental benefit from irrigation were expected to arise from vegetable cropping on 10% of 1 ha in the dry season. This was valued to a discounted MK1,500 over a 20-year period.

9. **Farm budgets.** Farm budgets for the cropping pattern used in the economic analysis showed that the gross returns per hectare of irrigation at the farm level were about MK630 per annum (Table 7). Adding a small vegetable plot on 1/10 ha, on-farm returns increased to approximately MK800 per annum/ha.

Table 5. Maize - Incremental Returns to Irrigation[2/]

	Year																					
	1989	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
Import Price[3/]	448	448	448	440	440	435	430	400	400	400	400	440	440	440	440	440	440	440	440	440	440	440
Freight	252	252	252	252	252	252	252	252	252	252	252	252	252	252	252	252	252	252	252	252	252	252
Marketing costs	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Import Parity	800	800	792	792	787	782	752	752	752	752	792	792	792	792	792	792	792	792	792	792	792	792
Value of output/ha																						
Rainfed (1.1t/ha)	880	880	871	871	865	865	827	827	827	827	871	871	871	871	871	871	871	871	871	871	871	871
Irrig. (2.5t/ha)	2,000	2,000	1,980	1,980	1,967	1,955	1,880	1,880	1,880	1,880	1,980	1,980	1,980	1,980	1,980	1,980	1,980	1,980	1,980	1,980	1,980	1,980
Cost of Inputs:																						
Rainfed:																						
Fert.	52	56	60	65	69	72	74	77	81	83	85	87	87	87	87	87	87	87	87	87	87	87
Seed	22	22	23	24	25	26	27	28	28	29	29	30	30	30	30	30	30	30	30	30	30	30
Labour	93	93	93	93	93	93	93	93	93	93	93	93	93	93	93	93	93	93	93	93	93	93
Total costs	167	171	176	182	187	191	194	198	202	205	207	210	210	210	210	210	210	210	210	210	210	210
Irrigated:																						
Fert.	147	183	189	195	200	205	211	217	223	230	239	249	249	249	249	249	249	249	249	249	249	249
Seed	25	26	27	27	27	28	28	29	30	31	32	33	33	33	33	33	33	33	33	33	33	33
Labour	131	131	131	131	131	131	131	131	131	131	131	131	131	131	131	131	131	131	131	131	131	131
Total costs	303	340	347	353	358	364	370	377	384	392	402	413	413	413	413	413	413	413	413	413	413	413
Net Return																						
Rainfed	713	709	695	689	678	674	633	629	625	622	664	661	661	661	661	661	661	661	661	661	661	661
Irrigated:	1,697	1,660	1,633	1,627	1,609	1,591	1,510	1,503	1,496	1,488	1,578	1,567	1,567	1,567	1,567	1,567	1,567	1,567	1,567	1,567	1,567	1,567
Increm. Benefits Irr.	984	951	938	938	931	917	877	874	871	866	914	906	906	906	906	906	906	906	906	906	906	906
Net Present Value at 12%	7,045																					

2/ In MK; US$1 = MK2.8.

3/ FOT Free On Truck Zimbabwe.

Table 6. Rice - Incremental Returns to Irrigation[4/]

	Year																					
	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Import Price[5/]	680	670	660	650	645	640	630	620	615	610	605	600	595	595	595	595	595	595	595	595	595	595
Freight	250	250	250	250	250	250	250	250	250	250	250	250	250	250	250	250	250	250	250	250	250	250
Marketing costs	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Export Parity[2/]	335	320	310	300	295	290	280	270	265	260	255	250	245	245	245	245	245	245	245	245	245	245
Gross Returns[6/]	1,005	960	930	900	885	870	840	810	795	780	765	750	735	735	735	735	735	735	735	735	735	735
Cost of Inputs:																						
Fertilizer	175	179	185	190	195	200	205	208	210	214	217	219	219	219	219	219	219	219	219	219	219	219
Seed	52	51	50	50	49	49	48	47	46	46	46	46	45	45	45	45	45	45	45	45	45	45
Labour	187	187	187	187	187	187	187	187	187	187	187	187	187	187	187	187	187	187	187	187	187	187
Total costs	414	417	422	427	431	436	440	442	443	447	450	452	451	451	451	451	451	451	451	451	451	451
Net Return/ha	591	543	508	473	454	434	400	368	352	333	315	298	284	284	284	284	284	284	284	284	284	284
Cropping intensity (0.6)	355	326	305	284	272	260	240	221	211	200	189	179	170	170	170	170	170	170	170	170	170	170
Net Present Value at 12%	1,946																					

4/ In MK; US$1 = MK2.8.

5/ Regional Market.

6/ Based on 3 t/ha.

Table 7. Calculation of Gross Returns to Irrigation[a/]

	Rainfed Maize	Irrigated Maize	Irrigated Rice
Yield kg/ha	1,100	2,500	3,000
Price MK/kg	0.24	0.24	0.30
Gross Returns (MK)	264	600	900
Variable costs (MK):			
Seed	25	29	19
Fertilizer	37	104	121
Agro-chemicals	0	14	0
Transport	16	36	66
Credit charges	9	18	15
Total variable costs (MK)	87	200	221
Gross Margin (MK/ha)	177	400	407
Gross returns from irrigation (MK)	631		

[a/] In MK; US$1 = MK2.8.

Ranking of Options

10. In order to devise an irrigation strategy the types of irrigation technologies that are economically viable needed to be identified given the incremental benefits to irrigation under Malawian conditions. The benefits calculated above were compared with the incremental costs of the various technological options discounted by the same factor of 12% over 20 years. This enabled the assessment of the amount that could be spent per hectare on irrigation over a 20-year project period and still achieve a rate of return of 12%. The thirteen different options of irrigation developments identified were then set out in order to increasing costs of irrigation per hectare (with some slight modification for considering recurrent cost implications and ease of implementation and operation), in order to facilitate the drawing of "cut off" lines below which technologies were not viable. This was a major element in devising the recommended strategy. The ranking is shown in Table 8.

Table 8. Ranking of Options

Option	Cost			Discounted	Implementation Ease	Operation Ease
	Investment	Annual	Recurrent[a/]	Total Cost[b/]		
	……………………… MK/ha ………………………					
1. Self-help schemes	800	138	80	1,320	3	2
2. Small electric pump	1,000	80	none[c/]	1,420	1	1
FINANCIAL LIMIT COMMON CROPS						
3. Low lift diesel pump	1,250	560	none	3,160	2	3
4. Portable petrol/kerosene pump	1,600	640	none	3,960	1	3
FINANCIAL LIMIT SPECIAL CROPS						
5. Shallow tubewell - electric	3,000	1,440	80	3,920	4	2
6. Shallow tubewell - diesel	2,000	1,200	80	4,180	4	3
ECONOMIC LIMIT COMMON CROPS						
7. Reservoir self-help	8,500	1,190	80	9,080	4	2
8. Petrol/kerosene with sprinkler	2,000	2,250	none	10,160	1	3
9. Shallow tubewell - petrol/kerosene	3,600	2,240	80	10,200	4	3
ECONOMIC LIMIT SPECIAL CROPS						
UNECONOMIC SCHEMES						
10. Deep tubewell - electric	10,000	2,200	80[c/d/]	15,880	5	2
11. Government scheme	14,000	2,040	500	15,560	5	6
12. PROPOSED PROJECT	23,000	3,050	620	18,660	6	6
13. Shire valley pump scheme	24,500	4,265	800[d/]	31,340	6	6

[a/] Assuming no water charges
[b/] Over 20 years at 12%.
[c/] Recurrent cost of production and transmission not considered.
[d/] Electricity charges borne by farmers.

US$1 - MK2.8

Selection of Options

11. From Table 8 it can be seen that without vegetable or other high value crops, irrigation would be financially viable to the farmer essentially only if pursued through self-help schemes and small electric pumps. If vegetables were included in the cropping pattern only the first 4 options could be pursued on a cost recovery basis.

12. The economic analysis suggests that, broadly, technologies up to shallow tubewells (Option 6) could be exploited on the basis of irrigation on existing widespread cropping patterns. Under special circumstances where high value crops such as vegetables can be marketed, more costly technologies such as the use of petrol/kerosene pumps and reservoir schemes may be economically justifiable (up to Option 9). However, the exploitation of such technologies would need to be based on individual appraisals and these technologies could not be recommended for widespread strategic adoption.

13. Table 8 also indicates that the proposed 20,000 ha scheme ranked twelfth in the list of options and that its cost was considerable above the "economic limit with special crops". In addition, the implementation and operation of that scheme was regarded as one of the most difficult of all options. The proposed project was therefore given low priority for financing on economic and managerial grounds. Instead, a revised and composite project proposal was prepared consisting of elements of the first 9 options only.

2. LAND DEVELOPMENT FOR ORCHARDS ON STEEP SLOPES (November 1989)

1. Establishing orchards in hilly areas often involves the construction of terraces in order to facilitate agricultural practices and reduce soil erosion. Since a considerable amount of earth will have to be moved, either a large number of labourers, with or without animal power, or mechanized equipment such as bulldozers would have to be used.

2. The construction of terraces involves the following:

- a topographical survey of the area to be terraced;
- a soil survey;
- a survey of the existing surface drainage;
- detailed designs and working drawings of the complete works;
- earthmoving;
- construction of risers;
- surfacing of risers;
- construction of pick-up ditches;
- construction of drainage outlets and channels.

3. The amount of earth to be moved depends upon slopes. On average, 3,000 to 4,000 m^3/ha should be expected for slopes varying 15 to 18º. Also width of terraces is dependent upon slopes. As generally one row of trees is placed on each terrace about 3-4 m width are required. Vertical spacing of terraces is then a function of slope. Most terraces are constructed with both longitudinal and cross slopes to facilitate sub-surface and surface drainage of rain water.

4. Bench terraces usually expose the infertile subsoil which could result in lower production unless some improvement measures are taken. Practices are to excavate a 1 m wide and 1 m deep ditch along the centre line of the terrace. The bottom of the ditch is sloping in line with the longitudinal slope of the terrace and its lower end is connected to a drain system. If necessary, rocks are being blasted. Stones and rocks excavated from the terraces and from ditch construction are being used to reinforce the risers of the terraces where necessary.

5. The excavated ditches are being filled with a 10 cm layer of organic material which may be of various origins such as grass, leaves, etc. and serves largely for drainage purposes. Where soils are heavy, this layer should be replaced by gravel or rocks on the uphill side of the ditch to ensure a more efficient drainage system. To avoid plugging by soil, some organic material should be placed on top of the gravel. Gravel and stones are normally excavated during ditch construction and thus readily available on site. A 15 cm layer of soil is placed on top of the organic material or gravel/rock layer followed by about 200 kg/ha of fertilizer. This, again, is covered repeatedly by a soil layer and a fertilizer application until the ditch is filled. Total amount of fertilizer applied may reach about 2,000 kg/ha. The type of fertilizer depends upon the inherent solid fertility.

6. After the ditch is filled to the top, the new soil is tilled and planted with a leguminous crop. At maturity it is ploughed under and left to decompose for about 6 months. Thereafter the planting ground is considered ready for transplanting of seedlings.

7. The total operation requires about 2,500 to 3,000 labour-days of work at a total cost of about US$2,500/ha (China) of which excavation and riser construction works account for 50%, fertilizer for 33% and the other soil improvement measures including protection of the risers for 17%.

8. The presented practice of land development for orchards has proven successful on a large scale in China.

Refer also to: Use of Bulldozers for Terracing in Irrigation Water Management Briefs No. 51.

3. OPTIMIZING IRRIGATION INVESTMENTS THROUGH SIMULATION STUDIES (November 1989)

(A Case Study)

Introduction

1. This paper intends to introduce the use of simulation techniques to optimize irrigation investments by way of an example for a large-scale irrigation scheme in India. The inter-relationships between the various future users and the opportunities to invest funds for improved irrigation performances were complex and could not be understood without a comprehensive system simulation study.

The Need for Investment

2. The project had a command area of about 94,000 ha of which only 65,000 ha received water on average during a year. In addition a further 5,000 ha were irrigated unauthorized outside the official command area boundary. The project irrigated thus 70,000 ha on average but irrigation facilities existed for about 99,000 ha. The shortfall of 29,000 ha was in the tail-end of the authorized system. It was the objective of the proposed project to rectify this discrepancy. How this could be achieved, however, was unclear at the beginning of the investigation.

The Physical Settings

3. **Two reservoirs** in tandem supplied water to the project area. The upper one (Reservoir 1) had a live storage of 840 Mm^3 and the lower one (Reservoir II) of 480 Mm^3. Reservoir I was constructed essentially to provide water to a large city and to generate electricity. However, the reservoir had been completed recently and no experiences as to its effect on the lower lying irrigation scheme was available. Some irrigation also took place between the two reservoirs. Provision of water supply t the city had priority over irrigation and irrigation had priority over power production. However, power would be produced also during the irrigation off-season, provided that Reservoir II would not spill.

Water supply from Reservoir I was as follows:

Month	Mm^3
June	20
July	30
August	32
September	33
October	35
November	29
December	17
January	24
February	23
March	27
April	17
May	24
Total	**311**

4. Over the study period of 20 years siltation of Reservoir I would be 7 Mm^3/year, most of which would be settled in the live storage area. This would affect the area/capacity curve in future as shown below:

	Year 1		Year 20	
Storage Level	**Storage Capacity**	**Reservoir I Area**	**Storage Capacity**	**Reservoir I Area**
	Mm^3	**ha**	**Mm^3**	**ha**
1	24	680	5	34
2	32	1,026	13	437
3	45	1,480	17	834
4	63	2,018	25	1,315
5	86	2,664	29	1,904
6	116	3,428	59	2,611
7	155	4,482	98	3,627
8	206	5,677	130	4,765
9	268	6,763	192	5,813
10	342	7,944	247	6,956
11	425	8,787	330	7,780
12	517	9,672	403	8,665
13	621	11,438	507	10,489
14	750	14,361	617	13,506
15	842	16,260	709	16,260

Since the silt load of the river would be retained in Reservoir I, no significant storage capacity would be lost in Reservoir II located just 90 km downstream.

5. The **main canal capacity** was designed for 97 m^3/s at full supply level. However, due to siltation and deterioration of the canal banks and structures, the main canal capacity had declined to about 76 m^3/s. The proposals made by the project authorities included upgrading of the main canal to allow at least a delivery of 83 m^3/s. The simulation study has taken this value into account (see below).

6. The area authorized for various **crops** compares to those actually grown as follows:

Crop	Authorized Area	Average Irrigated Area	Deficit
	ha		
Paddy under Canals	57,384	30,628	26,756
Paddy under Tanks (1/3 canal fed)[a/]	22,238	21,126	1,112
Sugarcane	14,000	12,709	1,291
Unauthorized[b/]		5,537	-5,537
Total	93,622	70,000	**23,622**
Deficit in Authorized Area			29,159

[a/] Small reservoirs inside the command area having their own catchment but still depending upon canal water support.
[b/] The unauthorized area was mainly under paddy.

7. The cropping calendar for the without project and the proposed with project case are shown below. Paddy under the canals and paddy under the tanks were grown at the same time. Sugarcane, however, was grown at three different growing periods.

Crop	Cropping Calendar	
	Without Project	With Project
Paddy under Canals	August-December	July-November
Paddy under tanks (1/3 canal fed)	August-December	July-November
Sugarcane 1	December-December (12 months)	same
Sugarcane 2a	Yr 1 August-October (15 months)	same
Sugarcane 2b	Yr 2 August-October (15 months)	same

The Simulation Study

Objective

8. The objective of the simulation study was to evaluate water availability and optimize its use for the main irrigation area under the new set of conditions, which would be radically different from those in the past due to the construction of the upper dam. As the future water availability for the irrigation area would allow a number of agricultural options - such as the ratio of area coverage under irrigation during the wet and dry seasons, changing of cropping patterns and cropping calendars - the study was to determine the most productive solution within the existing socio-economic framework.

Essential Features

9. The study was programmed in Lotus 1-2-3 spreadsheet which was familiar with the local project preparation cell. The first 2 years of the 20 year study (beginning with June 1967) have been reproduced in Table 1 to allow the reader to follow the inter-relationships between the various factors at play and copy the methodology applied for similar situations in other projects. The mathematical inter-relationships (formulae) are given in Table 2.

10. The study commences by determining the future inflow into Reservoir I from historic data collected at Reservoir II (Columns 2 to 5). Increased upstream use over the next 20 years from neighbouring States have been considered (Column 4). The planned and actual possible releases from Reservoir I (water supply and irrigation upstream and downstream of Reservoir II) determine, together with inflow and reservoir evaporation, the monthly reservoir balance of Reservoir I (Column 13). Spills from Reservoir I are shown for information in Column 14. It should be noted that releases for the irrigation system from Reservoir I (Column 9) were only made if they could not be met from Reservoir II balance or its own inflow. This allowed the maximization of power production from Reservoir I through maximizing the hydraulic head on the turbines.

11. Inflow to Reservoir II (Column 19) was determined from historic data minus that retained at Reservoir I plus a certain percentage of irrigation return flows (15% of the releases shown in Column 8). The calculation of the crop water requirement and deduction of the effective rainfall led to the net irrigation requirement in Column 33 for the cropping pattern and calendar as shown in paras 6 and 7. The irrigated areas of the various crops are shown in Columns 34 to 40. For these crops only the area of the canal irrigated paddy was considered as an option for change, since the paddy under tanks is geographically fixed and sugarcane expansion is not considered in future.

12. From the net irrigation requirement and the area cropped, the irrigation requirement was determined in Columns 42 to 47. Up to 24 Mm^3/month of this requirement was expected to be met by groundwater if a deficit occurred either due to canal capacity constraints or water deficits at the source. The use of groundwater is estimated in Column 49. However, use of groundwater was not considered to be available for project operation,

and releases of irrigation water (Column 50) did not consider groundwater resources. Considerations of groundwater use had only been made to allow indications of likely crop deficits incase the study would be used to estimate future productivity of different options (Column 56). The inflow to Reservoir II minus evaporation from the reservoir and the releases, led to a new monthly Reservoir II balance (Column 54).

13. In January the water availability for a possible dry season irrigation (in addition to sugar cane) (Column 59) was determined from the estimated reservoir balances of both reservoirs in May (Columns 13 and 54, e.g. 778 Mm^3) after considering evaporation losses between January and May, expected future urban water supply releases from Reservoir II (Column 57) and two irrigation supplies to tanks (Column 58) of 56 Mm^3[7]. The amount of water needed to irrigate a dry season crop over a certain area (Column 60, e.g. 429 Mm^3) was deducted from the reservoir balance of **both** reservoirs and the remaining water stored in Reservoir II and shown at the end of May in each year in Column 54 (row between the water years, e.g. 350 Mm^3). The crop water requirement for a dry season crop was taken at 600 mm at the crop and applied with a 42% delivery efficiency.

Options Investigated

14. Computer runs clearly indicated that the main effect of Reservoir I on the irrigation system was a reduced water supply during the wet season and an increased water availability during the dry season. It was therefore concluded that one scenario would be to reduce the authorized wet season area (say by 30,000 ha) and to formally establish a dry season area in the remaining area - which would also largely cover the present gap area. Another scenario would be to maximize the wet season area (the status quo) and provide irrigation for the dry season over an area that would vary according to water availability.

15. The **wet/dry season scenario** was investigated for 4 different options over a period of 20 years as follows:

Option No.	**Main Canal**	**Dry Season**	**Wet Season**	**Total**
	m^3/s	**……………………… ha**		………………………
1	76	30,000	69,159	99,159
2	83	30,000	69,159	99,159
3	90	30,000	69,159	99,159
4	83	20,000	79,159	99,159

7 This procedure of calculations is not truly following simulation techniques but was adopted to reduce programming time. It provided fairly accurate results.

The **wet season maximization scenario** was operated for the existing irrigation area of about 90,000 ha (authorized plus unauthorized area) with 2 options of main canal capacities (76 and 90 m^3/s).

Results

16. Results of the 4 **wet/dry season scenario** options are shown in Table 3 and indicate that reducing the area to be irrigated during the wet season by 30,000 ha to 69,159 ha would allow the present main canal capacity of 76 m^3/s to fully provide the available water both during the wet and dry season. In this scenario on average about 78,000 ha per year or 79% would be irrigated of which about 60,000 ha would be irrigated during the wet season and about 18,000 ha during the dry season.

17. Reducing the area to be irrigated during the wet season by only 20,000 ha would result in a decreased dry season area on average by about 5,000 ha to 13,000 ha while the average wet season area would increase by almost the same amount to about 65,000 ha. Thus, total annual area would be on average also 78,000 ha irrigated. From the aspect of total area covered per year no significant difference would exist therefore between the selection of 20,000 ha or 30,000 ha irrigated during the dry season.

18. The results of **maximizing the wet season area** are shown in Table 4 for two options of 76 m^3/s and 90 m^3/s main canal capacity. On average over 20 years total area irrigated for the 76 m^3/s option would be 87,300 ha and for the 90 m^3/s, 88,550 ha. Thus, the larger canal capacity would allow irrigation of an additional 1,250 ha yearly. This difference may be regarded as insignificant and would probably not justify the needed investments for upgrading of the main canal. However, compared with the wet/dry season scenario and additional 10,000 ha and above could be irrigated. The difference can be attributed to reduced spill and less evaporation from the reservoirs when maximizing the wet season area.

Strategies and the Proposed Operational Plan

Strategies

19. The reduction of the wet season irrigation area by some reasonable amount equal to about the present average gap area (29,000 ha) would improve reliability of supply to the reduced wet season area since emergency operations throughout the command area to provide water to the tail-end areas would significantly reduce. In addition water presently used with low efficiency at the tail-end during the wet season (which is entirely under paddy) could be stored in future for a much higher dry season productivity. Furthermore, should a carry-over policy be adopted (water brought forward from one wet season to the next for an early wet season start), less water would need to be stored under this alternative. In summary the advantage of this strategy is clearly a more manageable irrigation operation.

20. The main disadvantage of this strategy is a less efficient use of overall water

resources with a loss of about 10,000 ha potentially irrigable. In addition this strategy would require an official change of the authorized crop areas into a reduced wet season and a distinct dry season area (the balance area). However, it is anticipated that both future wet season and dry season irrigators would welcome such change. The wet season irrigators would have advantages as mentioned above, while the dry season irrigators would obtain assured dry season water in the future (within the limits of water availability, see Table 3) which would allow them to grow two crops per year (wet season rainfed plus dry season).

21. The works required for this strategy would consist of improving the water distribution in the dry season designated area and ensuring that the main canal outlets are watertight to allow closure of the wet season area during the dry season.

22. The alternative strategy to maximise the wet season area (as is authorized plus the unauthorized area presently being irrigated) would provide about 10,000 ha more irrigated than the wet season/dry season scenario (7% during the wet season and 14% during the dry season for the 76 m^3/s main canal option) but at a considerable variance (Table 4).

23. If it would be the intention to rotate the dry season areas yearly throughout the command area, considerable investment would be required to prepare the irrigation infrastructure for this operation (unless paddy is proposed also during the dry season - but then the area irrigated would reduce considerably).

Proposed Investments

24. Considering the two major alternatives of operating the system in future it must be clearly understood that the establishment of a more easily manageable wet/dry season operation would be at the cost of reducing the yearly potential irrigation area by about 10,000 ha even though about 8,000 ha would be gained compared to the past performance. However, the loss of potential irrigable area would be largely recuperated by the country, as most of the unutilized water would augment supplies in the irrigation systems downstream. Therefore the wet/dry season operation was selected leading to an investment plan as follows:

(a) delineation of 30,000 ha for dry season operation;

(b) provision of carry-over irrigation for nurseries to allow a timely start with early monsoon rains;

(c) upgrading of outlet shutters along the main canal;

(d) upgrading of the distribution network in 30,000 ha (largely identical with present gap areas) to allow dry season irrigation for non-paddy crops by means of proportional distribution.

No investments would be needed for main canal capacity increases, as the present capacity of 76 m^3/s would be adequate.

25. Development of operational procedures for cases of limited water supplies, such as rotational irrigation during the wet season (as has been done in the past) or reduction of numbers of irrigation given during the dry season would need to be done. A yearly alternating supply by area for the dry season, however, (say, for half supply of water only half the dry season area would be authorized in Year 1) is not considered practicable as the repetition of matching water supplies is of low frequency (see Tables 3 and 4) and would thus deteriorate farmers discipline.

Table 1-1. Simulation Study of a Combined Singur and Nizamsagar Operation (1967-1987) - SINGUR

Year/ Month	Histor. Inflow Niz.S.[8/]	Sing Gross Yields[9/]	NCR. Future U/S Use[10/]	Future Inflow	Planned		Actual		Res. Area[11/]	Eva. Loss	Total 8+9+11	Balance S. Reserv. 4-9	Spills	Deficit			Net Yield Intermediate Catchm. Area
					D/S Use[1/]	Releases to Niz.S.	Use Drink+ Irrigation	Release to Niz.S						Singur	Niz.s.	Total	
	Mm^3	Mm^3	Mm^3	Mm^3	Mm^3	Mm^3	Mm^3	Mm^3	ha	Mm^3	Mm^3	Mm^3	Mm^3	Mm^3	Mm^3	Mm^3	Mm^3
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
YEAR 1																	
June 67	99	104	4	100	20	38	20	38	6,763	13	72	283	0	0	0	0	4
July	2,132	1,654	4	1,650	30	0	30	0	16,260	25	55	842	1,036	0	0	0	492
Aug.	452	420	4	416	32	0	32	0	16,260	22	54	842	361	0	0	0	56
Sept.	1,133	927	4	923	33	0	33	0	16,260	20	52	842	871	0	0	0	230
Oct.	585	531	4	527	35	0	35	0	16,260	22	57	842	471	0	0	0	82
Nov.	51	99	4	95	29	0	29	0	16,260	19	47	842	47	0	0	0	0
Dec.	69	61	4	57	17	0	17	0	16,260	16	33	842	24	0	0	0	14
Jan. 68	21	67	4	63	24	0	24	0	16,260	20	44	842	19	0	0	0	0
Feb.	89	84	0	84	23	0	23	0	16,260	22	46	842	38	0	0	0	13
March	147	144	0	144	27	0	27	0	16,260	30	57	842	87	0	0	0	15
April	1	21	0	21	25	0	25	0	14,361	28	53	810	0	0	0	0	0
May	7	29	0	29	17	0	17	0	14,361	32	50	790	0	0	0	0	0
YEAR 2																	
June	26	56	8	48	20	0	17	0	6,713	13	30	274	0	3	0	3	0
July	163	194	8	186	30	0	30	0	8,734	14	44	416	0	0	0	0	0
Aug.	15	84	8	76	32	32	32	32	8,734	12	76	416	0	0	0	0	0
Sept.	526	482	8	474	33	0	33	0	16,260	20	52	835	2	2	0	0	66
Oct.	490	464	8	456	35	57	35	57	16,260	22	114	835	343	343	0	0	52
Nov.	61	98	8	90	29	0	29	0	16,260	19	47	835	43	43	0	0	0
Dec.	26	40	8	32	17	0	17	0	16,260	16	33	834	0	0	0	0	0
Jan.	8	30	0	30	24	0	24	0	16,260	20	44	820	0	0	0	0	0
Feb.	0	34	0	34	23	0	23	0	14,316	20	43	811	0	0	0	0	0
March	0	14	0	14	27	0	27	0	14,316	27	53	771	0	0	0	0	0
April	0	9	0	9	17	0	17	0	14,316	28	45	735	0	0	0	0	0
May	0	8	0	8	24	0	24	0	11,407	26	50	693	0	0	0	0	0

8/ NIZ.S. = Reservoir II.
9/ SINGUR = Reservoir I.
10/ U/S = upstream; D/S = downstream.
11/ RES. = Reservoir area.

Table 1-2. Simulation Study of a Combined Singur and Nizamsagar Operation (1967-1987) – NIZAMSAGAR

Year/ Month	Total Inflow Niz.S.	Crop Water Requirement					Rainfall	Eff.R.Fall		Net Irrigation Requirement					
		Paddy 1.half	Paddy 2.half	S.C 1[a/]	S.C 2a	S.C 2b		Paddy	S.C	Paddy 1.half	Paddy 2.half	S.C 1[12/]	S.C 2a	S.C 2b	Total
		.... mm													
1	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33
YEAR 1															
June 67	45			241	253	0	160	128	120			121	133	0	254
July	1,532	300	175	199	199	0	374	262	243	169	44	0	0	0	213
Aug.	423	143	116	174	165	68	184	147	138	69	42	36	27	0	174
Sept.	1,105	104	103	156	121	61	113	90	85	59	58	71	36	0	224
Oct.	558	106	108	171	109	67	6	5	5	104	106	167	105	63	543
Nov.	52	93	91	144		74	0	0	0	93	91	144	0	74	402
Dec.	40			64		89	7	6	5		0	59	0	84	143
Jan. 68	23			84		144	12	10	9		0	75	0	135	210
Feb.	54			85		176	19	15	14		0	71	0	162	233
March	106			97		237	29	23	22		0	75	0	215	291
April	4			137		153	4	3	3		0	134	0	250	384
May	3			223		289	1	1	1		0	222	0	288	511
YEAR 2															
June 68	3			241	253	0	125	100	94			147	159	0	307
July	4	300	175	199	199	0	231	162	150	219	94	49	49	0	411
Aug.	37	143	116	174	165	68	46	37	35	124	98	140	131	34	525
Sept.	72	104	103	156	121	61	204	143	133	33	32	23	0	0	88
Oct.	457	106	108	171	109	67	75	60	56	76	78	115	53	11	332
Nov.	47	93	91	144		74	41	33	31	77	75	113	0	43	308
Dec.	3			64		89	0	0	0		0	64	0	89	153
Jan. 69	4			84		144	0	0	0		0	84	0	144	228
Feb.	4			85		176	0	0	0		0	85	0	176	261
March	4			97		237	2	2	2		0	96	0	236	331
April	3			64		89	3	2	2		0	62	0	87	149
May	4			84		144	5	4	4		0	80	0	140	221

12/ S.C. = Sugar Cane.

Table 1-3. Simulation Study of a Combined Singur and Nizamsagar Operation (1967-1987)

Year/ Month	Area Irrigated								Irrigation Requirement						Use from G. Water[13/]	
	P. Canal		P. Tank		S.C 1	S.C 2a	S.C 2b	Total	P-Canal[14/]	P-Tank	S.C 1	S.C 2a	S.C 2b	Total		
	1.half	2.half	1.half	2.half											Required	Allowed
	ha								Mm³							
1	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49
YEAR 1																
June 67					10,293	2,416	0	12,709			30	8	0	37	0	0
July	3,532	17,662		10,563	10,293	2,416	0	40,934	25	5	0	0	0	29	0	0
Aug.	35,324	35,324	21,126	21,126	10,293	2,416	2,416	69,159	70	14	9	2	0	95	0	0
Sept.	35,324	35,324	21,126	21,126	10,293	2,416	2,416	69,159	74	15	17	2	0	108	0	0
Oct.	35,324	35,324	21,126	21,126	10,293	2,416	2,416	69,159	132	26	41	6	4	209	12	12
Nov.	35,324	17,662	21,126	10,563	10,293		2,416	40,934	87	17	35	0	4	144	0	0
Dec.					10,293		2,416	12,709			14	0	5	19	0	0
Jan. 68					10,293		2,416	12,709			18	0	8	26	0	0
Feb.					10,293		2,416	12,709			17	0	9	27	0	0
March					10,293		2,416	12,709			18	0	12	31	0	0
April					10,293		2,416	12,709			33	0	14	47	0	0
May					12,500		2,416	14,916			66	0	17	83	0	0
YEAR 2															0	0
June 68					10,293	2,416	0	12,709			36	9	0	45	0	0
July	3,532	17,662	2,113	10,563	10,293	2,416	0	40,934	44	9	12	3	0	67	0	0
Aug.	35,324	35,324	21,126	21,126	10,293	2,416	2,416	69,159	140	28	34	8	2	211	14	14
Sept.	35,324	35,324	21,126	21,126	10,293	2,416	2,416	69,159	40	8	6	0	0	54	0	0
Oct.	35,324	35,324	21,126	21,126	10,293	2,416	2,416	69,159	97	19	28	3	1	148	0	0
Nov.	35,324	17,662	21,126	10,563	10,293		2,416	40,934	72	14	28	0	2	116	0	0
Dec.					10,293		2,416	12,709			16	0	5	21	0	0
Jan. 69					10,293		2,416	12,709			21	0	8	29	0	0
Feb.					10,293		2,416	12,709			21	0	10	31	0	0
March					10,293		2,416	12,709			23	0	14	37	0	0
April					10,293		2,416	12,709			15	0	5	20	0	0
May					12,500		2,416	14,916			24	0	8	32	0	0

13/ G + Groundwater.

14/ P = Paddy.

Table 1-4. Simulation Study of a Combined Singur and Nizamsagar operation (1967-1987)

Year/ Month	Release From Reserv. N2	Res. Area N2	Eva. Loss N2	Total Change	Res. Balance N2	Surplus Reserv.	Deficit Crop	Drink. Water From N.Z.	Tank Feeding From N.Z.	Water Avail. for Rabi[15/]	Water Used for Rabi	Rabi Area	Release to Rabi
	Mm^3	ha	Mm^3	Mm^3	Mm^3	Mm^3	Mm^3	Mm^3	Mm^3	Mm^3	Mm^3	Mm^3	Mm^3
1	**50**	**51**	**52**	**53**	**54**	**55**	**56**	**57**	**58**	**59**	**60**	**60**	**61**
YEAR 1			5		22								
June 67	37	1,581	3	5	27	0	0						
July	29	14,016	22	1,481	504	1,004	0						
Aug.	95	14,016	19	309	504	309	0				30,000 ha RABI		
Sept.	108	14,016	17	980	504	980	0						
Oct.	197	14,016	19	342	504	342	0						
Nov.	144	12,421	14	-107	397	0	0						
Dec.	19	12,421	12	9	406	0	0						
Jan. 68	26	12,421	15	-19	387	0	0	3	28	778	429	30,000	36
Feb.	27	12,421	17	10	397	0	0	3					95
March	31	13,201	24	51	448	0	0	3	28				159
April	47	13,421	25	-68	380	0	0	3					139
May	83	10,173	23	-103	276	0	0	3					
YEAR 2	0		23		350								
June 68	45	10,173	20	-63	287	0	0						
July	67	7,397	12	-74	213	0	0						
Aug.	197	2,146	3	-163	50	0	0						
Sept.	54	2,786	3	15	65	0	0						
Oct.	148	12,421	17	292	357	0	0						
Nov.	116	10,173	12	-81	275	0	0						
Dec.	21	8,734	9	-27	248	0	0						
Jan. 69	29	7,397	9	-34	214	0	0	3	28	446	429	30,000	36
Feb.	31	7,397	10	-38	176	0	0	3					95
March	37	4,978	9	-42	134	0	0	3	28				159
April	20	3,933	8	-25	109	0	0	3					139
May	32	2,786	6	-35	74	0	0	3					

15/ Rabi = Dry season.

(Editor's Note – regrettably the below Tables could not be reproduced in this PDF edition of the document.)

Table 2. Formula Used for Simulation (Page 1)

Table 2. Formula Used for Simulation (Page 2)

Table 3. Simulation Results of 4 Scenarios for All Wet and Dry Seasons

Year	76 m^3/s 30,000 ha			83 m^3/s 30,000 ha			90 m^3/s 30,000 ha			83 m^3/s 20,000 ha		
	Rabi Area[16/]	Crop Deficit	Kharif Area[17/]	Rabi Area	Crop Deficit	Kharif Area	Rabi Area	Crop Deficit	Kharif Area	Rabi Area	Crop Deficit	Kharif Area
	ha	Mm^3	ha	ha	Mm^3	ha	ha	Mm^3	ha	ha	Mm^3	ha
1967		0	69,159		0	69,159		0	69,159		7	79,159
1968	30,000	0	69,159	30,000	0	69,159	30,000	0	69,159	20,000	12	79,159
1969	30,000	25	69,159	30,000	25	69,159	30,000	25	69,159	20,000	0	79,159
1970	30,000	0	69,159	30,000	0	69,159	30,000	0	69,159	20,000	10	79,159
1971	30,000	0	69,159	30,000	0	69,159	30,000	0	69,159	20,000	0	79,159
1972	23,524	402	34,580	23,524	402	34,580	23,524	402	34,580	20,000	511	31,664
1973	0	52	62,243	0	52	62,243	0	52	62,243	0	66	63,327
1974	30,000	0	69,159	30,000	0	69,159	30,000	0	69,159	20,000	0	79,159
1975	30,000	0	69,159	30,000	0	69,159	30,000	0	69,159	20,000	0	79,159
1976	30,000	0	69,159	30,000	0	69,159	30,000	0	69,159	20,000	9	79,159
1977	22,548	179	41,495	21,738	179	41,495	21,738	179	41,495	20,000	273	31,664
1978	0	0	69,195	0	0	69,159	0	0	69,159	0	0	79,159
1979	30,000	85	55,327	30,000	85	55,327	30,000	85	55,327	20,000	50	71,243
1980	970	0	69,159	0	0	69,159	0	0	69,159	0	13	79,159
1981	7,197	67	62,243	6,217	67	62,243	6,217	67	62,243	2,632	81	63,327
1982	28,445	144	34,580	28,445	144	34,580	28,445	144	34,580	20,000	176	31,664
1983	11,779	24	69,159	11,779	24	69,159	11,779	24	69,159	10,298	24	79,159
1984	30,000	46	62,243	30,000	46	62,243	30,000	46	62,243	20,000	46	71,243
1985	0	387	13,832	0	387	13,832	0	387	13,832	0	506	15,832
1986	0	80	62,243	0	80	62,243	0	80	62,243	0	91	63,327
1987	0			0			0			0		
Average	18,223	75	59,477	10,085	75	59,477	18,085	75	59,477	12,647	94	65,702

16/ Rabi = Dry season.

17/ Kharif - Wet season.

Table 4. Simulation Results of 2 Kharif Options for 99,000 ha Main Canal Capacities of 76 and 90 m^3/s

Year	76 m^3/s			90 m^3/s		
	Crop Deficit	Kharif Area[18/]	Rabi Area[19/]	Crop Deficit	Kharif Area	Rabi Area
	Mm^3	ha	ha	Mm^3	ha	ha
1967	99	85,000		63	90,000	
1968	226	70,000	51,000	226	70,000	50,000
1969	89	85,000	13,000	52	90,000	11,000
1970	103	85,000	39,000	67	90,000	37,000
1971	142	75,000	41,000	142	75,000	39,000
1972	732	34,000	7,000	732	34,000	4,000
1973	92	80,000	0	92	80,000	0
1974	179	70,000	42,000	179	70,000	41,000
1975	31	95,000	36,000	31	95,000	35,000
1976	141	75,000	51,000	105	85,000	50,000
1977	447	41,000	19,000	447	41,000	17,000
1978	56	88,000	0	20	90,000	0
1979	308	55,000	28,000	272	55,000	26,000
1980	107	85,000	0	70	85,000	0
1981	187	62,000	0	151	62,000	0
1982	237	35,000	25,000	237	35,000	24,000
1983	24	97,000	0	24	97,000	0
1984	276	62,000	39,000	275	62,000	38,000
1985	766	14,000	0	766	18,000	0
1986	130	62,000	0	98	75,000	0
1987			0			0
Average	219	67,750	19,550	202	69,950	18,600

18/ Kharif - Wet season.

19/ Rabi = Dry season.

4. CANAL LINING WITH PLASTIC FILMS (March 1990)

1. Considerable experiences over a period of 17 years exist with plastic film lining in China. Because of its low cost, quick installation and longevity, it is a very attractive alternative to conventional concrete, slabs or brick lining. This paper summarizes principles and practices as observed in China and indicates cost involved for large scale applications.

2. Plastic lining is used in two modes depending upon the erosion hazard of the canal to be lined:

-. plastic lining installed in earth canals 25 to 50 cm below canal profile if water velocities are < 1 m/s). The depth of installation is a function of canal size;

-. plastic lining underneath concrete lining if water velocities are > 1 m/s. This mode is based on the observation that concrete lining tends to crack after some time - partly due to temperature differences of 90ºC - and that the plastic lining prevents leakage after the cracking has occurred.

Side slopes of plastic lined and earth covered canals are generally constructed 1:2. To prevent slippage, trees (poplars and willows) are planted at the edge of the plastic film to allow roots to develop below **and** above the plastic sheets. In addition to preventing slippage of soil this allows a self-irrigation of the trees in desert areas. To avoid root penetration of the plastic films these are treated with chemicals during the production process.

3. Typically the plastic films are made of polyethylene (PE) and are 0.16 mm thick. Sheets come in 5x50 m or 7x50 m dimensions. While these sheets should be welded together to make a fairly watertight film, this had not been done in the past and losses through the canal bed still occurred. Measured data have been summarized in the table below and indicate that lining reduced losses between 48 and 75%. It can be expected that welding of individual sheets, including around structures,would reduce water losses further, in fact if done properly down to negligible amounts if water uptake by the trees is discounted.

Losses per km (%)

Type of Canal	Unlined	Plastic Lined	Reduction in Losses (%)
Conveyance Canals			
East Bank	0.42	0.19	55
West Bank	0.46	0.24	48
Main Canals			
1.	0.59	0.15	75
2.	0.69	0.20	71
3.	0.60	0.21	65
Branch Canals	2.5	not appl.	
Lateral Canals	6.0	not appl.	
Source. Tarim Basin Irrigation Project, Yerqiang Scheme, China.			

4. Lining has been done very selectively, in two ways:

- where seepage losses were highest, and
- only for part of the cross section in canals with varying discharge (the project was a run-of-river scheme).

This minimized leakage losses during low flows but allowed groundwater replenishment during high flows for tree growth other than those planted on the canal banks).

Cost

5. The plastic sheeting was priced at US$0.27/m^2 and movement of 1 m^3 of soil out and into an existing canal was about US$1.2. Total cost of earth covered various sized canals,including some minor structures (5 m^3 of concrete per km and some gates) were as follows:

Canal Capacity	Plastic Film Used per Km	Cost per km	Cost per m^2 of plastic lined canal bed	Cost per m^3 capacity per km
m^3/s	m^2	………………………… US$ …………………………		
100	32,000	100,000	3.1	1,000
118	58,000	140,000	2.4	1,186
120	23,000	73,000	3.1	608

6. The cost of concrete lined canals with plastic lining underneath, based on 40 cm sand and concrete slabs of 5 cm thickness on canal bottoms and 15 cm on sides (slope 1:1,75), were as shown below:

Canal Capacity	Plastic Film Used per km	Cost per km	cost per m^3 Capacity	Remarks
m^3/s	m^2	US$	US$	
80	48,000	240,000	3,000	Constructed
20	18,000	77,000	3,850	Projected

The cost difference between plastic lining and concrete lining (with plastic underneath) is considerable as apparent when comparing the cost tables. No wonder therefore that 94% of a proposed canal lining programme was to be installed with plastic film only.

5. REHABILITATION OF SMALL EARTHDAMS (April 1990)

1. Small reservoirs or tanks are often constructed by self-help means, under emergency situations or employment programmes. The resulting quality of the dam is not always as desired, since neither a proper clay core has been constructed, nor compaction been properly executed. As a result the dams leak and may be unstable and thus do not fulfil their desired function. A remedy is needed. This paper describes a successful method of dam grouting as practised in China.

2. The grouting material consists of a 90% clay and 10% cement mix which is being injected into boreholes (percussion drilled) of 100 mm f, drilled in two parallel but staggered rows on top of the dam, 2 m apart. The holes along the rows are 4 to 6 m apart. Each hole penetrate the dam's body and the underlying pervious layer until an impervious layer - rock or clay - is reached. The clay-cement mix is injected with 2 kg/cm^2 of pressure. The effect of the grouting operation is shown in the Figure below using a typical design. Leakages observed in a number of cases have been reduced by about 50%.

3. Cost per km has been US$162,000 (China). Water saved per km was 190 l/s enabling about 190 ha to be cultivated with a total net return for long staple cotton of about US$300,000/year (at US$1,580/ha). Thus, the investment cost could be recuperated including a profit within one season.

(Editor’s note: The drawing ‘Effect of Grouting Operations’ could not be reproduced in this PDF edition of the document.)

6. MODERN IRRIGATION EQUIPMENT AND WATER SHORTAGE (May 1990)

1. Use of traditional irrigation methods in water short areas appear to be wasteful when compared to the potential use of modern irrigation methods such as sprinkler, trickler or bubble irrigation. That this is not necessarily true is discussed in this paper which is based on findings in northern Yemen where investment in modern irrigation equipment was suggested to overcome water shortages.

Water Resources for Irrigation

2. Groundwater and surface water were the main water resources in the project area. Groundwater was over-exploited dropping annually between 1 to 7 m. Surface water was fully used and practically no water escaped into the sea.

Present Irrigation Methods

3. Most groundwater-based irrigation schemes in the mountainous part of the project area used piped conveyance systems often in connection with hose-type laterals for distribution to individual plots. Irrigation (pumped or river-diverted) along the rivers (wadis) and on the high plains was largely done through open conveyance channels and field channels. On-farm distribution was mainly through flood irrigation, but furrow (potatoes, vegetables) and border strip (fruit trees, coffee) methods were used as well.

Irrigation Water Use Efficiency

4. Two major aspects were at the origin of irrigation water use efficiency. The first was that farmers tended to over-irrigate because they lacked knowledge on crop water requirements. Secondly, they tended to compensate poor land levelling with over-watering (since cheaper). Losses in conveyance were less pronounced than was generally believed, particularly where farmers used piped conveyance systems. Efficiencies varied therefore, depending on the farmers perspective on crop needs, size of plots and conveyance systems. In addition, cropping seasons made a difference, since over-watering was reduced during the hot periods due to capacity constraints. Estimates on water use efficiencies ranged from 10% (particularly in perennial run-of-river schemes) to 70% under some pump irrigation schemes during the summer. Contrary to what it may appear, the lower range of values did not represent a drastic loss of the water resource, since most of the water not used by the crops found its way back to the aquifer or river and thus was not entirely lost.

5. Evidence of this irrigation return flow either to the aquifer or to the river was available - in the case of groundwater - from the reaction of groundwater levels to rainfall and experience from other countries with similar subsoils (most irrigation systems need an artificial drainage system because irrigation water return flow induces groundwater levels to rise). Return flows to the river was even more obvious as the irrigated plots were only about 2 m above the water level, less than 200 m away from the river and underlaid by gravel.

6. Over-irrigation, either due to over-watering or poor land levelling reduced crop productivity. Most farmers were not aware of this. Low productivity in such cases resulted

from lack of root aeration as well as leaching of soil nutrients. This phenomenon was typically seen in run-of-river schemes, where yields of maize were not much above 1 ton/ha even with fertilizer applications, while yields of more than 3 tons/ha should be achievable. Evidence of this low water productivity (yield per m^3 of water consumed) was also noticeable under pump-irrigation schemes although less pronounced.

7. Solving the above problems was best done through extension service; in other words, through the dissemination of appropriate irrigation water management know-how. Following better irrigation practices would also save labour and reduce pumping times considerably.

8. Increasing the water use efficiency by either employing extension methods or modern irrigation equipment would, however, have negative results on the water resources if the improvements would lead to expansion of irrigated areas, which in many cases it would. This fact is explained with the increased consumption of water by the irrigated crops and a reduced irrigation return flow from the total irrigated area.

9. In order to demonstrate the mechanism involved, two typical cases have been presented below - one for a run-of-river system and another for a pump scheme system.

Case 1 - Run-of-River Irrigation

Present Situation

Irrigation efficiency: 30%
Area presently irrigated: 1 ha
Type of crop: maize
Crop density: 50% of optimum
Crop water requirement per season: 500 mm or 5,000 m^3/ha
Water diverted: 5,000/0.3 - 16,700 m^3
Return flow to wadi: 90% of losses - (16,700 - 5,000) x 0.90 - 10,500 m^3
Water consumed: 6,200 m^3 (crops and evaporation)

Future Situation (after installation of a furrow system and introduction of a water management extension package)

Irrigation efficiency: 65%
Type of crop: maize
Crop density: 80% of optimum
Crop water requirement per season: 600 mm or 6,000 m^3/ha
Water diverted: 16,700 m^3 (as at present)
Area irrigated: 16,700 x 0.65/6,000 - 1.8 ha
Return flow to wadi: 90% of losses - 16,700 - (1.8 x 6,000) x 0.90 = 5,300 m^3
Water consumed: 11,400 m^3 (crops and evaporation)

Increase in water consumption under the improved situation is 5,200 m^3 or about double the present use from the wadi.

Case 2 - Pump Irrigation

Present Situation

Irrigation efficiency: 50% (based on earth channel conveyance)
Area presently irrigated: 2 ha
Type of crop: wheat, potatoes
Crop density: 80% of optimum
Crop water requirement per season (120 days): 450 mm or 4,500 m^3/ha
Water pumped: 2 x 4,500/0.5 - 18,000 m^3
Return flow to aquifer: 80% of losses - (1,800 - 9,000) x 0.8 = 7,200 m^3
Water consumed: 10,800 m^3 (crops and evaporation)

Future Situation (after installation of pipe hose system and introduction of a water management extension package).

Irrigation efficiency: 70%
Type of crop: wheat, potatoes
Crop density: 90%
Crop water requirements per season (120 days): 480 mm or 4,800 m^3/ha
Water pumped: 18,000 m^3 (as at present)
Area irrigated: 18,000 x 0.7/4,800 - 2.6 ha
Return flow to aquifer: 80% of losses - (18,000 - (2.6 x 4,800)) x 0.8 = 4,400 m^3
Water consumed: 13,600 m^3 (crop and evaporation)

Increase in water consumption under the improved situation is 2,800 m^3 or about 26% more.

10. The above examples indicate the need for more water resources when expanding the irrigation area based on improved irrigated efficiency. The same is true, of course, also when expanding without improving irrigation efficiencies. Since water is limited, expansion should therefore not be aimed at and instead the efficiencies increased on the existing area. In this case, water consumption would probably not change significantly either way since increased transpiration from higher cropping densities (increased leaf area) would balance reduced evaporation from soil surfaces.

11. Under a non-expansion strategy, benefits would result from higher productivity (as in the above two cases) and from reduced pumping time in case 2 above, which would have been only 75% of the present situation.

12. In monetary terms a reduction of 25% in pumping costs was equivalent per year at 3,240 hours of operation for a 5 l/s discharge between US$415 to 1,075 as shown below:

Pumping Depth	Operating Cost	
m	Total	25%
	………………………… US$ …………………………	
20	1,660	415
40	2,250	560
60	2,820	705
80	3,300	825
100	3,400	975
120	4,300	1,075

Use of Modern Irrigation Equipment

13. Introduction of piped distribution systems, such as sprinkler, trickle and bubbler irrigation was attractive only to those farmers whose potential irrigation system capacity had limited their expansion possibilities. This was usually the case when about 60 or 70% of water use efficiency through better irrigation water management had been reached. However, at that point it was questionable whether investments of up to US$7,000/ha would be warranted by an increase of water use efficiencies of a mere 15 to 20%.

14. Modern irrigation equipment was not attractive to those farmers who could not expand their irrigated area due to a lack of land. These farmers had a lot to gain, however, from better water management, as pumping cost would decrease and yields increase without the need for large investment. If inputs and marketing were the constraints at present, rather than land, modern irrigation equipment would not be helpful of course in any case.

15. Considering the national point of view, the use of modern irrigation equipment was not in the interest of the country either, since the depletion of groundwater resources in the high plains would accelerate, and only temporarily benefit a few farmers. In the mountainous areas the use of modern irrigation equipment would shift agricultural production uphill through increased water abstraction and loss of irrigated agriculture downstream. This would imply that eventually the better agricultural lands in the country which were downstream would be adversely affected at the benefit of the potentially less productive areas upstream.

Conclusion

16. In conclusion, investments in modern irrigation equipment under the described circumstances of limited water resources, high installation cost and cheaper options through better water management, could not be proposed.

7. SHALLOW GROUNDWATER DEVELOPMENT (September 1990)
(A Case Study)

Introduction

1. Shallow groundwater is found in many parts of the world as evidenced by numerous dug wells and small tubewell developments. Many of these wells are used for domestic water supply as well as for irrigation of small plots employing either human-powered, animal-powered or mechanized pumps. The exploitation of the groundwater resources is, however, often below its optimum as to the type of well used, the lifting devices employed and groundwater potential. This paper discusses options for development of an area underlain by shallow groundwater which was only partially used even though the need for water was considerable.

2. The area investigated for this study belongs to what is collectively called the Sahelian zone in southern Niger. Precipitation averages between 400 mm in the northern parts and 800 mm in the extreme south. Rainfall infiltration is high due to the predominately sandy soil and to the intense individual rainfalls. Estimates of replenishable groundwater in this zone exceeds 500 million m3/year which is virtually unused. This is surprising since the depth to groundwater is generally only 6 to 8 m, rendering the water easily exploitable. Yet, in spite of the considerable water resources available, the area is generally considered to be typical of desertic, water deficient zones.

Present Development

3. **General.** Groundwater is being used for domestic water supply and some limited irrigation. Water for irrigation is drawn from dugwells, lined dugwells, tubewells and, although rarely, through artesian pressure. Water lifting is achieved by hand, animals, as well as by motor pumps. Hand-operated pumps include bucket and rope systems (calabasse/gourd), a counter weight assisted bucket system (chadouf) and a recently introduced bailer type system to extract water from tubewells. The latter system is a cleverly designed (by Lutheran World Relief Organization - LWR) bailer-tube of about 80 cm length which fits neatly into the tubewell casing. Water enters into the tube through a foot valve (flap type) at its bottom and the whole apparatus is lifted out of the tubewell with a rope.

4. Lifting by animals was not observed during the field visit but its existence was reported. The reader is referred, therefore, to the FAO/AGL paper no. 43 on "Water Lifting Devices" which describes most existing systems in detail including power capabilities of various species, food requirements and coupling animals to water lifting devices.

5. The motor pumps used are generally of 3 to 5 hp capacity portable petrol powered pumps. Electric powered pumps are rare due to lack of an electricity network.

6. The total number of wells and their annual extraction in the area has not been determined. It was clear, however, that each village had at least one dugwell. In addition, the LWR - Organization has installed about 3 000 tubewells. Furthermore, a few agricultural projects obtain their water from deep tubewells.

7. Irrigation by hand - either from dugwells or tubewells - is limited to surfaces of

600 to 1,000 m2, depending upon the lift encountered and the soil to be irrigated (conveyance losses). At 7.5 m lift, about 8 m3 per day can be pumped by one person as is shown in the graph below. This amount corresponds to an irrigation depth of between 6 to 10 mm per day, considering 75% distribution efficiency.

(Editor's Note – regrettably the below Figure could not be reproduced in this PDF edition of the document.)

Figure 1

WATER LIFT (m)

SOURCE: Irrigation Water Management Brief No. 66, FAO 1984.

8. Irrigation with motor pumps is limited either by water availability from the rather shallow wells or by the gravity distribution system used, which generally consists of earth channels feeding small bunded plots of 2.5 x 2.5 m square. Under these conditions only an area of 3,000 to 5,000 m2 can be irrigated.

9. **Construction of tubewells.** The tubewells constructed by the LWR-Organization have all been rotary drilled using a hand-operated soil auger type device with which about 12 m depth can be reached. Construction time is about one day using two locally trained-persons. Deeper wells are drilled using either rotary or percussion rigs and reach depths of 100 m and more.

10. **Crops** grown under irrigation are largely cash crops including onions, fruit trees (mango), tomato, spices, sugarcane (for chewing) and sweet potatoes. It was reported that wheat, cotton and sorghum were being irrigated during the cool season.

11. **Financial considerations.** The extreme poverty of the rural population make financial considerations the outstanding issue for future development of groundwater. Though dugwells do not need much financial outlays if self-made, they require hard work and thus extra food requirements for the farmer. Since unprotected dugwells collapse periodically, they are a constant drain on such resources as money, labour and food supply.

12. Lined permanent dugwells are expensive with a price tag starting from about US$600; thus out of reach for average farmers. Shallow tubewells cost about US$60 to 90 each, which is still considered high by farmers. All lined dugwells and tubewells visited had been constructed with subsidies. Consequently, farmers had paid only between US$60 for lined dugwells (EC donated) or US$20 for tubewells (LWR donated).

Options for Development

13. The ease with which groundwater could be developed in the southern part of Niger through the installation of low-cost shallow tubewells (ref. the LWR approach), indicated that a large-scale tubewell programme could be considered. Under such a programme, dugwells could not be recommended as the tubewells were cheaper, could provide more water if necessary (by drilling deeper) and the water quality could be better preserved for domestic supplies. The argument that water cannot be bailed from tubewells has been demonstrated as invalid as mentioned above.

14. **Drilling** the tubewells could be done in a number of ways including jetting (also termed washboring), percussion drilling and hand or power rotary drilling. The cheapest of these methods is probably the rotary drilling by hand (US$60/well including casing) as practised under the LWR project. However, maximum depth of drilling is restricted to about 16 m and soils have to be sandy or silty. Clay or gravel layers would be an obstacle to this method. Jetting of a well would cost about US$90/well including casing, with even more restrictions if clay or gravel would be encountered. Power rotary drilling (3 hp hand-held rig)[20] would overcome these restrictions and would allow drilling to greater depth. Percussion drilling would have the same advantages, but - if done by hand - is hard work and requires a crew of about 6, while the hand -held rotary rig can be operated by only 2 persons (even one person, if a rig-stand is provided). Cost of a hand-held rotary drilled well probably does not exceed the washbore well much (US$120/well) considering that the drilling failure rate due to the presence of clay and gravel is nearly zero. The percussion rig will, however, increase the cost of a well to about US$600, according to information collected from Nigeria. Consequently, it was proposed to use only hand and power rotary drilling equipment. Each rig could drill three wells per week (including construction of the filter and casing) or about 100 wells per year (allowing for some slippage). Considering 10,000 tubewells to be drilled and divided equally between the two drilling methods, a total of 25 rigs of each type would be required for a 2 year drilling programme. The cost of one hand rotary drill is about US$200 and that of the hand-held power rotary about US$1,600[21/] . Thus, the total cost of 25 rigs of each type of system would cost US$5,000 for the hand rotary and US$40,000 for the power rotary. In addition, each 5 units should be equipped with a 4-wheel drive vehicle to carry the drilling equipment, casing and filters to the construction site. For each power rotary equipment an additional motor pump would be required (US$600 with fittings) as well as a 10 m2 plastic sheet to allow the construction of recirculation reservoirs (US$20) at the construction site (water for drilling would be transported with oil drums). Total cost of the power rotary equipment would thus amount to US$55,500 and, together with the hand rotary equipment, to US$60,500. Adding 20% spare parts and 30% shipping cost, total cost would be about US$95,000. The 10 vehicles would cost about US$155,000. Thus, the investment cost would be of the order of some US$250,000 before considering expenses for O&M of the vehicles and drills, as well as for staff and possibly camping equipment, which may amount to about US$100,000 for a two-year implementation programme.

15. **Water lifting** could be done by hand or by motor pumps. Since electrification is non-existent in the rural areas, internal combustion motors would have to be used (see paras. 17 and 18 below). Lifting by hand provides those farmers who are not able to afford a motor pump immediately - or are unwilling to take the risk of a pump - with the chance to start

20 Ref. also Irrigation Water Management Brief No. 98, FAO 1988.

21/ Ex factory Deep Rock, USA.

irrigation of a small garden initially. This allows them both to gain experiences of irrigated agriculture and an opportunity to save money for the purchase of a motor pump at a later date. However, it should be remembered, that pumping by hand is not free, but requires energy as well. Since this energy is provided by food, it is generally more costly than that obtained from a motor pump. The graph below shows, for instance, that about 20% of the produce of irrigated millet (at 8 m lift) would be needed for incremental human energy requirement to run the lifting device. Farmers are very well aware of this relationship. In addition, the graph indicates that the energy requirement of an employed operator (without considering a wage) could hardly be met from irrigated millet if lifting of water would exceed 8 m.

(Editor's Note – regrettably the below Figure could not be reproduced in this PDF edition of the document.)

Figure 2

WATER LIFT (m)

SOURCE: Irrigation Water Management Brief No. 66, FAO 1984.

16. Water lifting by animals from tubewells would not increase water delivery much above human capacity, since the diameter of the bailer is restricted by the size of the casing of the tubewell and the length of the bailer which could not be extended much beyond what a human power could lift (i.e. 1 m length). Thus, animal power would be completely underutilized and is therefore not recommended.

17. Water lifting with motor pumps provides a number of options as to type of engine and type of pump. The cheapest combustion type engine per m3 of water pumped is generally the diesel engine -largely because of its longevity and low fuel cost. However, diesel engines are not easily available below 5 hp and at considerable initial cost (from US$600-Indian made + shipping cost). Furthermore, they are heavy and thus not easily carried to and from wells. All these points disqualify the diesel engine for the proposed type of irrigation development in which an engine of not more than perhaps 1 to 2 hp would be sufficient. The next smallest combustion type engine of about 3 hp is a petrol or a petrol/kerosene engine. The latter has the distinct advantage of lower fuel cost, as follows:

Type of Fuel	Official Price	Unofficial Price
	.... US$/l	
Kerosene	0.36	0.21
Petrol	0.84	0.45
Diesel	0.68	0.27

18. At US$0.36/l, the official price for Kerosene is thus some 20% cheaper than the unofficial price for petrol. This makes such engines rather attractive for farmers. Kerosene engines are available in the market (Niamey) for about US$625 (4.3 hp, Suzuki including a self-priming pump) and smaller capacity engines exist elsewhere and should cost about US$400 including a centrifugal pump.

19. **Pumps.** Hand-operated tubewells could use the bailer type device mentioned above. Motor driven pumps could choose between self-priming centrifuged suction pumps (< 8 m lift), centrifugal suction pumps with foot valve (〈 8 m lift) and jet pumps (〉 8 m lift). Progressive cavity pumps are not recommended as they are not only expensive but also tend to get stuck when impurities (sand, silt) enter through the proposed simple filter arrangements (slots only).

20. The self-priming centrifugal pumps have the advantage of not needing any water for priming - but this is at a price. In contrast, the foot valve-operated pumps need water for priming and this may be difficult to obtain. The cost of these pumps alone is about US$150 to 100, respectively and the foot valve unit would thus cost about US$50 less than a self-priming unit. The jet pump would have the advantage of being an underwater pump and thus not restricted by suction limits. Even though the pump is very common in household applications it is seldom used for irrigation purposes mainly because of its low efficiency. However, since yields from small tubewells in the project area would not greatly exceed 10 m3/h, the available engine sizes of about 3 hp would exceed by far the power requirements. The low efficiencies, therefore, would only increase the cost of pumping by a small margin, or not at all, as the more efficient pumps may, in any case, have to be throttled to avoid emptying the well. This, in fact, is a common practice.

21. For the unfamiliar reader, the figure below, taken from a Sears Catalog, shows a cross section of a jet pump and the total assembly. Other designs are available. It should be noted that a jet pump has to be coupled to a primary pump (eg. centrifugal pump), thus the cost of the jet pump (about US$80) is in addition to the cost mentioned above (as well as the cost of longer pipes, if water is lifted from greater depth).

(Editor's Note – regrettably the below Figure could not be reproduced in this PDF edition of the document.)

Figure 3

22. **Distribution of Water.** Hand-operated tubewells could distribute water as at present, i.e. by gravity or by watering can, depending upon the soils encountered. These methods would allow the irrigation of 600 to 1,000 m2, as mentioned previously.

23. The distribution of water lifted with a motor pump could be done by gravity -if soils permit - or by plastic pipes (preferably Polyethylene - PE) in sandy soils. The gravity systems could augment their efficiency of distribution, if a reservoir would store a certain volume of water (eg. 2 m3) which would be released intermittently and in larger streams. In sandy soils such method could provide irrigation for about 3 500 m2 to 4,000 m2 while the gravity distribution in heavier soils (without the reservoir) probably would irrigate up to 5,000 m2. In order to augment the coverage to 5,000 m2 and above in sandy soils, pipes would be needed possibly together with a sprinkler system; that is 2 or 3 sprinklers either on tripods or on a hose pull type arrangement.

24. Sprinklers would be new in Niger and it is not known how farmers would accept them. Tests are therefore recommended. Such tests have been conducted in Pakistan through an FAO project (1977) with positive results. Details of that test have been recorded in FAO's Irrigation Water Management Brief No. 47. Irrigation of fruit trees and some row crops could be improved through a system of mini sprayers (20-40 l/h) which reduces water consumption since not all of the soil surface would be wetted. Drip irrigation would not be recommended since it is both capital intensive and subject to blockages. Lining of field channels would not be recommended either since it would be costly and generally of short duration (cracking and other physical damages). The extra energy required to generate the pressure needed for sprinkler or spray irrigation would be available from the otherwise over-dimensioned motor pump as shown in the example below:

Assumptions:
Kerosene engine with 3 hp rating
Dynamic suction head at pump = 10 m
Pressure required at hose entry = 3 atm
Total head = 40 m
Discharge = 10 m3/h
Horse power requirement for centrifugal pump

$$hp = \frac{10{,}000\ l \times 40\ m}{3{,}600\ sec \times 75\ kg/s \times 0.7\ eff.} = 2.1\ hp$$

25. In the case of a deeper well (below suction lift of 8 m) and the employment of a jet pump the following technical performance could be expected if the dynamic water level would rest at 12 m[22/].

Pump rating = 3 hp for 12 m lift and 5.4 m3/h for a hose entry pressure of 2.7 atm[23/].

22/ Taken from Sears Catalog (adjusted).

23/ Note the higher hp requirement for lower performance compared to the centrifugal pump.

26. The cost of a mobile PE-hose sprinkler distribution system covering 5,600 m2 based on 50 m main line of 40 mm diameter and 60 m hose laterals of 25 mm diameter with 2 sprinklers on tripods would be about US$400 including 30% for shipment. A hose-pull system (sprinkler on a sledge type support) and a mobile spray irrigation system would cost about the same. An expansion of area irrigated to 1 ha would add about US$200-250 for additional pipes, provided the shape of the farm is favourable. Otherwise sinking of one or two additional tubewells may be more cost effective, however, moving of main pipes would have to be considered.

Summary of Various Options and Area Irrigable

27. The various options discussed, their cost and the area irrigable with different systems are summarized in the Table below. The cost for motor pump-operated systems range from an investment of US$460 for 0.5 ha gravity irrigation to US$1,220 for 0,6 ha of sprinkler/spray irrigation. These cost correspond to US$920/ha to US$2,000/ha. O&M cost of the drilling operation may add US$20 to 30/ha. It should be noted, that the area irrigable was divided into "expected" and "potential" area irrigable with the belief (based on experiences) that the potential area irrigable would not be reached with the new technology by the average farmer during the initial period of a development programme (5 years).

Summary of Various Options, their Cost and Area Irrigable

Options	Individual Capital Investment (US$)	Total System Cost (US$)	Area Irrigable (ha) Expected Potential
Dug wells			
A. Unlined	40[24/]	40	0.06 0.08
B. Lined	600[1/]	600	0.06 0.1
Shallow Tubewells (12 m)			
A. Washbore	90[25/]		
B. Rotary drilled			
1. Hand powered	60[26/]		
2. Motor powered	120[27/] 600[2/]		
C. Percussion drilled			
1. Hand powered	600[2/]		
D. Lifting by hand			
1. Clay soils		80 to 140	0.08 0.1
2. Sandy soils		80 to 140	0.06 0.1
E. Lifting by motor pump	400		
1. Gravity distribution			
- clay soils		460 520	0.5 0.7
- sandy soils (without Reservoir)		460 to 520	0.3 0.3
2. Sprinkler/Spray System	400 to 650	860 to 920	0.6 1.0
Deep Tubewells (20m)	240[4/]		
A. Lifting by motor pump	480		
1. Gravity Distribution			
- clay soils		720	0.3 0.4
- sandy soils (without reservoir)		720	0.2 0.2
2. Sprinkler/Spray System	300 to 500	1,020 to 1,220	0.4 0.6

24/ Source USAID (adjusted).
25/ Quotation from Nigeria.
26/ Quotation from Niger (LWR-Project).
27/ Authors estimate using Hydro Drill.

8. PLANNING FOR UNDER-IRRIGATION (May 1991)

Introduction

1. The deliberate underwatering of crops when water is scarce or costly can be observed in many irrigation projects. For most public schemes such practices are explained with optimization of limited water resources, equity considerations, i.e. more farmers can benefit from a given amount of water, and that more productive land can be created for settlement. In private schemes under-irrigation is often practised to save on pumping or labour cost.

2. The scale of practised under-irrigation world wide is considerable and warrants reconsideration of the traditional approaches to irrigation project design, based on the assumption that the project would provide an assumed cropping pattern with all the water required for unchecked plant growth.

3. This paper intends to analyze in a broad sense under which situations, under-irrigation is advantageous and what are the factors to be considered for implementation. Three examples of planned under-irrigation practices are presented as well as the case of paddy and situations resulting from "unplanned" under-irrigation. In order to assist the unaware reader, the paper provides initially a conceptual background of crop response to water, and its economic opportunities.[28]

Crop Response to Water

4. Crop yield responses to soil moisture deficits vary with crops over a season and at different periods in the growth cycle of individual crops. Response curves for most common crops have been published in FAO's Irrigation and Drainage Paper No. 33 - Yield Response to Water, and elsewhere.

(Editor's Note – regrettably the below Figure could not be reproduced in this PDF edition of the document.)

Fig. 1. General Form of Crop Production Function

Fig. 1 illustrates a general relationship between irrigation water use and crop yield. The broken line represents the relationship between transpiration and yield, and the solid line represents the relationship between applied water and yield.

5. Although Fig. 1 relates yield to transpiration alone, it should be mentioned that the method of irrigation and irrigation scheduling can significantly affect yield independently of the amount of water used. For instance, water deficit during the flowering period has a considerable yield-depressing effect for most crops which cannot be recovered through full or additional irrigation at a later crop stage. On the other hand full irrigation during late cycle stages of some crops (e.g. for wheat at the grain filling stage) may be of no benefit or even detrimental.

28 For more details refer to Deficit Irrigation by Mr. English, Journal of Irrigation and Drainage Engineering, 1990.

6. The above water curve is divided into two zones. Zone 1 can be characterized as the under-irrigation zone, and Zone II as the over-irrigation zone.

7. When a small amount of water is applied it will be almost completely used by the crop as there will be little runoff or percolation. The transpiration and applied water curve will be roughly coincident. The applied water-yield relationship may be roughly linear up to approximately 50% of full irrigation.

8. At higher levels of applied water the crop production function begins to curve over, reflecting various water losses that develop as water use approaches full irrigation. Deep percolation increases with increasing applied water. If the increase in applied water is associated with higher irrigation frequencies, greater evaporation may occur with relatively little increase in yields. In a word, the irrigation system will become less efficient as water use approaches full irrigation. This decline in efficiency is largely associated with variability in applied water, crop characteristics, and soil characteristics.

9. The shape of the curve in Zone II is governed by other factors. Beyond the yield-maximizing point, the curve begins to decline as a consequence of such things as lodging, reduced aeration in the root zone, leaching of nutrients, and diseases associated with wet soils. The precise nature of that relationship will be a complex function of the timing of excess water applications, temperatures during the period of excess, and other factors. On the basis of these considerations, yields in Zone II might reasonably be approximated by a function that declines linearly with excess water use.

Revenue and Cost Functions

10. Since gross income is equal to crop yield multiplied by the crop price, the relationship between irrigation water use and gross income will have the same general shape as the applied water curve in Fig. I. The curvilinear revenue function of Fig. 2 represents such a gross income curve.

(Editor's Note – regrettably the below Figure could not be reproduced in this PDF edition of the document.)

Fig. 2. Revenue and Cost Functions

The level of irrigation that would maximize yield is shown as W_m in Fig. 2.

11. The straight line in Fig. 2 represents a cost function relating total production costs to applied water. The cost function has three important features. The first is its lower limit, the intercept with the vertical axis, which is associated with capital costs, taxes, insurance, and other fixed costs of irrigation, as well as fixed costs of tillage, planting, chemical use, and harvest. The second feature of the cost function is the slope, which represents the marginal variable costs of production. These include the variable costs of

irrigation, such as pumping costs, labour, and maintenance. Other costs may also vary with yield, as yield varies with water use. A farmer may adjust his fertilizer use in accordance with anticipated crop production, harvest costs may vary with yield, and so on. All such factors are embodied in the slope of the cost function. The third feature of the cost function is the upper limit, shown as the design capacity point in Fig. 2, which represents the maximum water delivery capacity of the system. Although the cost function is shown as a straight line in Fig. 2, it might be curvilinear in the real case.

12. If land is limiting, the optimum irrigation strategy would be to apply that amount of water which would maximize the net income derived from each unit of land; i.e. maximize the differential between the curves in Fig. 2. That amount, shown as W_l will be somewhat higher than W_m, since the two curves are diverging in the range to the left of W_m. If more water is used (W_m or W_o) the profit will be reduced as the curves converge. According to economic theory, W_l will be that point where the value of the marginal product just equals the marginal cost; that is, where the slope of the cost function equals the slope of the gross income curve.

13. If water use is reduced below W_l, a point will be reached (W_e) where the net income per unit of land will just equal the net income from full irrigation. Within the range between $W_m$and W_e profits will be greater than at full irrigation.

Opportunity Costs of Water

14. When the amount of land under irrigation is constrained by a limited water supply, the economic returns to water will be maximized by reducing the depth of water applied and increasing the area of land under irrigation until the sum of the profit from the under-irrigated land and the marginal profit from additionally irrigated land are maximized. W_w represents that point in Fig. 3.

15. Since the optimal level of irrigation when land is limiting (W_l) or when water is limiting (W_w) will be less than the yield maximizing level (W_m), capital costs might be reduced by designing a lower capacity system. Such a system might use smaller mainlines, fewer distribution laterals and smaller or fewer wells and pumps. The potential for increased profit is illustrated by Fig. 3, which shows an alternative cost function based on a distribution system designed for irrigation at level W_w.

(Editor's Note – regrettably the below Tables could not be reproduced in this PDF edition of the document.)

Fig. 3. Reduced System Capacity

Limitations

16. If the relationships shown in Figs. 1, 2 and 3 were known precisely it would be a simple matter to choose an optimum level of water use for any particular situation. However, while the cost function may be determined fairly accurately, the crop production function is highly variable and unpredictable. Given the variability of weather, soils, antecedent moisture, distribution uniformity, and other factors, it is difficult to predict how much water will be successfully stored in the root zone. When that uncertainty is combined with the variability of crop response to chemical use, weather conditions, disease, pests, and so on, the yield that will actually be produced by a given level of applied water becomes quite unpredictable. Such uncertainties imply economic risk. The project can mitigate the risk to some extent through water use strategies, crop rotations, and so on, but a substantial degree of uncertainty will remain and that uncertainty will confound any attempt to determine an optimum water use plan precisely. That is the essential problem with deficit irrigation.

Practised Under-Irrigation

17. The above conceptual background points toward economic and social opportunities. Commercially oriented irrigation projects generally tend to exploit the financial implications of under-irrigation, while public schemes, particularly in food deficit countries, tend to concentrate on the social gains from under-irrigation, i.e. that more people can benefit when water is spread over a larger area and - to a certain degree - on employment opportunities and maximizing (not optimizing) production from the given land and water resources.

18. The three examples given below exploit the opportunities of under-irrigation for three totally different objectives. One example from India is equity oriented, the one from China needs productive land for settlement and the last from Europe is economically oriented.

19. **India.** In northern India a system of rotational irrigation (Warabandi) has been developed during the last 100 years in which a limited amount of water is being applied to an area several times bigger than could possibly be irrigated, thus making sure that as many farmers as possible receive irrigation water. A typical application (e.g in the state of Haryana) is about 70 l/s for 420 ha or 0.17 l/s/ha or about one sixth of crop water requirement. To achieve the distribution of water each farmer has been given a specific length of time once a week for irrigation in proportion to his holding. Extra time is given for travel time of water and time is subtracted from the tailender for the advantage of winding up with a filled field channel. No extra time is given for seepage losses in conveyance from the outlet to a particular field.

20. The delivery canal system is operated to comply with crop water requirements as far as possible, e.g. the canals are operated either continuously, on weekly on-off basis or on multiple weeks on-off basis such as one week "on" and two weeks "off". Irrigation is carried out both at night and during the day. Lands are consolidated. Water availability is sufficient for irrigation of a proportion of each holding only. Therefore, a strong incentive exists for farmers to maximize utilization of the limited water supply.

21. The right of each farmer to his share of water is protected by law, and the local Canal and Drainage Act empowers canal officers to ensure implementation of the rational

water supply. For more information on the operational procedures refer to FAO Irrigation Water Management Brief No. 34, 1981).

22. No data are available on project economics for this type of irrigation system simply because of the planners overriding social obligations to optimize equity of resource distribution. The built-in incentive for farmers to use the limited amount of water efficiently has been discussed at length previously (refer also FAO Irrigation Water Management Brief No. 17, 1980) and can be summarized as follows:

(i) Optimizing returns through water efficient cashcrop selection, e.g. cotton rather than sugarcane or rice.

(ii) Improved irrigation technologies to increase efficiency of water distribution.

(iii) Incentive for maintenance of water courses and private investment into lining.

(iv) Improved land levelling.

(v) Adoption of night irrigation.

(vi) Improved interest in extension messages (e.g T&V).

(vii) Practising of fallow rotation to increase fertility.

(viii) Maximizing use of occasional rainfall, which on a fully irrigated field would be wasted as canal water could not be used elsewhere.

23. It should be added that considerable effort has been made in the past to also introduce the rotational distribution system and thus the planned under-irrigation to southern India. The prerequisite for such introduction would always entail a change in State laws (each State is autonomous in agricultural matters) to allow under-irrigation applications in the first place supported by administrative procedures for law enforcement and official lines of complaint for farmers. Disciplinary requirements by individual farmers would be secondary to the success of planned under-irrigation in the above circumstances. Despite considerable effort by the World Bank to assist in changing State laws to allow introduction of planned under-irrigation practices, no southern State has yet been able to introduce such change. The result has been a near chaotic type of under-irrigation (since water supply is nearly always insufficient for the adopted irrigation area) with severe strains on water use efficiencies (over-irrigation in head ends and little or no water in tail ends of the schemes) and disturbance of social peace.

24. **China**. In China under-irrigation aims often at increasing the productive land base for settlement of people. The extra cost involved for expanding the infrastructure and O&M to distribute the "saved" water from under-irrigation is absorbed under this aspect.

25. The degree and operation of under-irrigation and its operation typically for such cases is shown by an example from the Tarim area in Western China. The water allotted to three main crops compares to crop water requirements and irrigation requirements determined by FAO methodologies[29/] as indicated below:

29/ Ref. Report on the Expert Consultation on Revision of FAO Methodologies for Crop Water Requirements, 1990.

Crop Water Requirements

Crop	FAO Calculations		China Practices		
	Crop Water Requirements	Irrigation [a/] Requirements	Allotted Water	Water Saved	Yield [b/] Reduction
	mm			%	%
Cotton	706	723	558	23	19
W. Wheat	617	736	527	28	19
Maize	580	652	490	25	24

[a/] Difference between crop water requirements and irrigation requirements due to scheduling efficiency (not to field application losses).
[b/] Includes effect of 25 mm effective rainfall.

26. The table also indicates water savings between 23 to 28% and corresponding yield reductions between 19 and 24%.

27. Scheduling of water applications was also practised rather different from FAO recommendations as indicated in the case of cotton by the excessive length of intervals shown in the table below.

Irrigation Intervals of Cotton

Crop	Practised [a/]			FAO Recommended [b/]		
	Date	Amount	Interval	Date	Amount	Interval
		mm	days		mm	days
Cotton	Pre-irrigation	100		Pre-irrigation	100	
	25.3 Plant.	83	77	25.3 Plant.	73	55
	12.6	100	14	20.5	75	20
	26.6	100	28	10.6	75	15
	24.7	100	14	25.6	100	15
	08.8	75	33	10.7	75	15
	11.9 Harvest			25.7	75	15
				10.8	75	15
				25.8	75	16
				11.9 Harvest		
Total irrigation		558			723	
Total water available including effective rainfall		583			748	

[a/] Yield reduction of 19%.
[b/] No yield reduction.

28. The practices of irrigation under the selected under-irrigation regime were however judged to be close to optimum: leaching requirements to check salinity were done during early spring which left the soil profile at field capacity for germination and early growth. The first irrigation at about flowering avoided yield losses during that period. Subsequent irrigations satisfied crop water requirements only to about 70-80% but yield reductions during those periods - particularly during the ripening period - were less severe. Also the unusual and rather extended length of interval between irrigations appeared to be acceptable under the selected under-watering regime, as the individual doses of irrigation was increased which allowed maintenance of the deeper roots and thus increased uptake of nutrients. Furthermore the practice reduced evaporation from the soil surface.

29. The under-irrigation practices freed about 23% of the irrigation water for use elsewhere in the case of cotton and over 28% for wheat. Investment cost per hectare of expanded irrigation system was US$ 930. Net returns of the crops were as follows:

Net Returns of Fully and Under-irrigated Crops

Crop	**Fully Irrigated**	**Under-Irrigated**	**Difference**
	…………………US$/ha…………………		
Medium staple cotton	1,140	930	210
Long staple cotton	1,640	1,328	312
Wheat	350	283	67
Maize	117	89	28

30. Needless to say, that the production emphasis was on long staple cotton production but the crops were grown on the basis of a two-year rotation of cotton, follow-on winter wheat and maize. Productivity per unit of water due to under-irrigation increased from US$ 0.10/m^3 to 0.11/m^3 as shown below:

Productivity per Unit of Water

Crop	**2-year Period**			
	Fully Irrigated		**Under-Irrigated**	
	Volume m^3/ha	**Return US$/ha**	**Volume m^3/ha**	**Return [a/] US$/ha**
L.S. Cotton	7,230	1,640	5,580	1,328
W. Wheat	7,360	350	5,270	283
Maize	6,520	117	4,900	89
TOTAL	21,110	2,107	15,750	1,700
Return/m^3 (US$)	0.10		0.11	

[a/] Linear to yield reductions. Possible farm operational saving not considered.

31. The water saved could irrigate an area of about 25% more or 0.25 ha if considering 1 ha to begin with, which would return US$425 in 2 years (0.25 ha x US$1,700/ha). The total return of 1.25 ha thus figures US$1,700 + 425 = US$2,210 which needs to be compared to US$2,107/ha under full irrigation in 2 years. This represents a gain of US$18 in 2 years or US$9/year. The investment into the extended canal system and its O&M worked out to be about US$150/ha/year or US$38 for the 0.25 ha additionally irrigated. Thus, the overall return was negative (US$9 - 38 = - 29). Nevertheless, the project was accepted for implementation based on the overriding social benefits expected from settlement of people.

32. **Europe.** A third illustrative example concerns a pumped irrigation system in central Europe. The result of the study has been published in detail by Rydzewski[30/] and only a summary is given in this paper.

33. When considering modern, efficient, mechanized irrigation systems the cost of installation and operation becomes especially significant when irrigation is supplementary to rainfall. For instance, if it is assumed that 50% of the crop water requirement is met by rainfall, then a deliberate 10% reduction in total water application represents a 20% reduction in water provided by the planned irrigation facility, pointing clearly to possibilities of substantial reduction in costs.

34. The Cost/Benefit Analysis will thus concern itself with relating, through the irrigation water productivity function, the costs of delivering and applying water at a given level and the benefits of the consequent agricultural production. Four elements were distinguished in the analysis:

(i) the determination of the productivity of irrigation water, i.e. the agricultural output, expressed in terms of values as the gross benefit of the project;

(ii) the estimation of on-farm production costs, considered as a negative benefit, to derive the net benefit of the project;

(iii) the estimation of the cost of delivering irrigation water to the project boundary;

(iv) the estimation of the cost of distributing and applying this water to the cropped land.

35. The **productivity of irrigation water** was expressed as a mathematical representation of the relationship between water (the input) and crop yield (the output) in a crop production process, as explained earlier. Once the crop yield per unit area had been determined, the gross benefit was obtained by multiplying it by the farm-gate price. This could be in market prices for a financial analysis, in border prices for an economic (efficiency) analysis and, as a further step, incorporating distribution weight effects for a social (equity) analysis. In the example used a financial analysis was adopted. The on-farm production costs had to be varied according to the degree of irrigation expected. Two aspects needed to be considered:

(i) where the costs were dominated by the area irrigated (e.g. the cost of land preparation, seed, fertilizer, weeding, harvesting, etc.), but which may also be

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30/ Irrigation Development based on Water Deficits, ICID Symposium, 1973.

influenced by the level of irrigation or of crop yield; and

(ii) where cost could be seen as influenced exclusively by the volume of the agricultural product, i.e. by the crop yield (e.g. the costs of transport and packing).

In the first group the total cost was considered to be directly proportional to the irrigated area and then modified by an appropriate coefficient. For fertilizer, a relationship was derived from the results of experiments which indicated fertilizer use versus water application/water requirement. Similar coefficients were obtained for the cost of seed (actual/maximum use), and the cost of harvesting (actual/maximum), both linked to the level of crop production (actual/maximum yield).

36. It was observed that, when the actual yield was more than 90% of maximum yield, the harvesting cost was already at its maximum. Costs items in the second group did not create any problems in this analysis since they were already related to the level of crop yields. Although these costs, per unit of yield, may decrease slightly as crop output increases, the effect was small enough to be ignored.

37. The **cost of irrigation water** greatly influenced project cost and it was therefore separated from the cost of water application. The approach was to assume that the project management would receive the water at a unit cost which would cover its provision. All costs (capital, replacement and O&M) were discounted over the chosen time horizon. The annual volume of water delivery, multiplied by the, as yet, unknown unit cost, was likewise discounted. The value unit cost was obtained by equating the present values of costs and benefits.

38. The **cost of distribution of water** included all capital and recurrent costs of providing and operating a system for distributing and applying irrigation water to the land. Since the intention was to study the economic consequences of designing irrigation projects with capacities below the maximum, it was essential to derive a cost-capacity response function, expressing relevant costs as a function of the design capacity.

39. The cost here would be influenced partly by factors outside the control of the designer, such as the climate, the topography and the soils, as well as by design decisions on the type of irrigation system. Thus, once the project area had been selected, interest turned to the cost-capacity response function for the various irrigation system alternatives under design consideration. For each alternative the relationship could be generalized approximately by expressing the cost of the system for a particular capacity as a percentage of the cost of providing maximum capacity.

40. The preceding sections showed the elements of the conceptual model for designing the irrigation project for water deficit. The project was proposed with the objective of increasing maize production. The peak demand capacity for supplementary irrigation was based on the difference between the estimates of crop consumptive use and of effective rainfall at a 90% chance of occurrence. The results were as shown below:

Description of irrigation requirements

Month	Consumptive Use (mm)	Effective Rainfall (mm)	Irrigation Requirement (mm)
May (20 days)	25	18	7
June	89	44	45
July	145	32	113
August	133	38	95
September (20 days)	38	11	27
TOTAL	430	143	287

41. Available soil moisture was assumed to be 150 mm/m depth of soil, with irrigation applied when 50% of the available moisture in the root zone was depleted. The soil moisture deficit at planting was assumed to be nil, whilst a 60 mm deficit was permissible at harvesting.

42. The project had an area of 18,000 ha and was 15 km long and 12 km wide. The rectangular shape lent itself to a layout for lateral-move irrigators which enabled a flexible approach to be adopted in the provision of supplementary irrigation, with possible changes in peak supply capacity at field level being achieved by varying the number of machines deployed. With this type of irrigation the investigation of the effects on project costs of reducing peak irrigation capacity entailed separate design exercises deploying a progressively smaller number of irrigator units over the project area. This was done for five cases, as set out in the following table:

Design Alternatives for 18,000 ha area

Case	Peak Irrigation Capacity (mm/month)	Machine Hydromodule (l/s/ha)	Area irrigated per Machine (ha)	Number of Machines
1	150 (maximum)	0.60	150	120
2	125	0.50	180	100
3	100	0.40	225	80
4	75	0.30	300	60
5	50	0.20	450	40

43. **Project Cost and Benefit.** Water cost delivered to the project area was calculated to be on average US\$ 0.02/m^3. Each irrigation machine cost US\$ 123,000 and had an assumed economic life of 15 years. Cost of canals was taken as US\$ 425/ha with a life expectancy of 20 years. O&M cost for the irrigation machines reduced as the numbers of machines decreased, but remained constant for the canal system.

44. **Gross Benefit**. Since only one crop, maize, was considered for the project, a typical farm-gate price (in financial terms) had to be assumed. But to introduce some degree of flexibility, three values of 0.13, 0.14 and 0.15 $/kg were introduced into the analysis.

45. **On-farm Costs**. A budget for one hectare under maize was drawn up, introducing whenever necessary the relations between cost and yield described above.

46. **Results of Optimization** are summarized in the following table for 10% and 12% discount rates and different values of under-irrigation. The example illustrates clearly how, **for mechanized irrigation which is supplementary to rainfall,** design of the irrigation facility for deliberate under-watering can be economically attractive or in some cases make a project economically attractive in the first place. Where economics improve with under-irrigation, lower initial investments or a larger command area can be expected from the same investment.

Project Net Present Value for different Design Capacities, Discount Rates and Maize Prices

Discount Rate	Cost of Water at Project Boundary ($/m^3)	Maize Farmgate Price ($/kg)	Net Present Value ($ million) at different Design Capacities (% of maximum Capacity)							
			30%	40%	50%	60%	70%	80%	90%	100%
10%	0.02	0.13	4.65	7.96	8.13*	7.37	6.32	4.70	3.00	0.85
		0.14	11.79	14.41	14.15*	12.96	11.56	9.54	7.46	4.86
		0.15	18.93	20.96*	20.16	18.56	14.79	14.37	11.92	8.87
12%	0.02	0.13	0.45	3.37	4.26*	3.81	3.05	1.78	0.44	-1.30
		0.14	6.55	9.33	9.41*	8.59	7.52	5.91	4.24	2.12
		0.15	12.66	14.93*	14.54	13.37	12.00	10.04	8.05	5.55
* = Highest Returns										

The Case of Flooded Paddy

47. When moisture content of the soil decreases to 70-80% of the saturation value, rice yields begin to decline. At a soil water content of 50% saturation, yield decrease is 50%-70%. At a soil water content of 30%, no yield can be expected and plants die when soil water content is below 20%. The yield reductions due to water deficit are thus more severe than experienced with other crops and saving of water based on plant physiological reactions to water stress is virtually impossible since evapotranspiration at a saturation value of 70 to 80% is little changed from that of a paddy standing in water. Besides, under-irrigation in this range would create a severe weed problem and yields would sharply decline for that reason. However, there are other opportunities to save water in the irrigation of paddy which are largely of a water management nature including reduction of percolation losses and losses through bunds. Up to 45% of water savings have been observed (particularly in lighter soils) when lands were left "dry" for several days after the disappearance of irrigation water while yield reductions were only about 10%. Experiences from Thailand and India indicate that yields even increased when paddy lands were kept "dry" occasionally during the vegetative period for 2 to 3 days. However, weed control became necessary. For more information on opportunities for planned under-irrigation on paddy (compared to standing water operations)

refer to FAO Irrigation Water Management Briefs Nos. 52 and 100.

Unplanned Under-irrigation

48. The above examples have indicated the benefits one can expect from planned under-irrigation. However, more often than not irrigation schemes planned for full irrigation turn out to be unplanned under-irrigation schemes, generally with disastrous consequences as described under the Indian example.

49. Two situations of unplanned under-irrigation arise virtually in all irrigation schemes planned for full irrigation and are due to the variability of the water supply. Generally, the planning for 75% probability of water availability (a) between years and (b) within a crop season indicate statistically that under-irrigation is accepted in one out of four years or seasons. Much has been written on this subject (ref. FAO, Irrigation Management Briefs) and it is important to remember that omission of planning for this type of "forced" under-irrigation is likely to lead again to chaotic irrigation practices when the situation arises - as it will. A rule of thumb may help the planner: small independent free-holder farmers will not tolerate the under-irrigation of standing crops by more than 25%, if their entitlement is to full irrigation by law. Those close to the water source will simply resort to self-help.

Conclusions

50. Planned under-irrigation may be economically attractive both for gravity and pumped irrigation schemes. It is always socially attractive where water resources are limited and equity or settlement objectives are paramount.

51. Planned under-irrigation needs careful study of the social environment in which it is to be operated. The very specific social conditions in India and China could not be easily applied elsewhere.

52. Planned under-irrigation of paddy is unlikely to be economically and socially rewarding.

53. Ignoring water availability variation during planning will lead to forced under-irrigation and is likely to result into chaotic irrigation practices.

9. INVESTING IN WATER USER ASSOCIATIONS (November 1992)

Introduction

1. The implementation of Land Reforms in former socialist countries affected their irrigation subsectors severely. Firstly, the break-up of the former cooperatives and State farms into numerous small private farms resulted in a loss of scale and operational order to contract, convey and deliver irrigation water, make arrangements for its payment, procure finances for new constructions and arrange organization of maintenance work, such as for reservoirs, canals, hydraulic structures and drainage systems. Irrigation systems in which the former cooperatives and State farms were responsible also for the water source such as reservoirs, pumping stations or wells were particularly affected and often ceased to function at all. Furthermore, with the loss of management, the loss of know-how of irrigation principles and practices was experienced with no irrigation extension set up yet to replace the former system, leaving the new farmers to their own devices. Consequently, Governments were confronted with the need to reestablish an organizational framework for irrigation matters - and generally in a hurry.

2. A number of options are available for such an organization within two extremes: either to employ governmental staff to manage the entire subsector or to hand the irrigation schemes fully over to private enterprises which will sell water to the farmers. While governmental take-over of the irrigation schemes is costly to the public, may not optimize resources and may even be conceived as undemocratic within the new socio-political environment, establishment of totally private water enterprises may not be functionable for some time either, despite the present drive in some countries to privatize all economic activities, including that of the irrigation subsector.

3. Regarding privatization of the irrigation subsector, the following experiences exist with **share holding type** of enterprises: a company would be formed, under the legal framework of private enterprises, in which farmers, other users, private professional organizations (Chambers of Commerce, Industry, Agriculture, etc.), public and private funding institutions, and possibly other type of investors would participate.

4. This type of association has been adopted in France and the Compagnie d'aménagement du Bas-Rhône Languedoc, la Société du Canal de Provence and the Compagnie des côteaux de Gascogne are good examples, although it must be said that after many years of existence the main shareholder is still the State.

5. There is also a legal conflict with this type of enterprise that would have to be resolved. It consists in the difficulty in delegating the authority of managing a public resource (water), to a private enterprise. Private enterprises may have the right to use the water but the custody of it should remain in the public domain. This generally complicates the operation and management for the company, mainly in the process of collecting revenues and application of sanctions to the users for incorrect use of the resource.

6. The reason why it is imperative for the State to maintain the custody of water includes the need to control the enterprises. This need is best illustrated through negative experiences in Chile: the accumulation of water rights by private hydropower developers for use in the future, "freezed" water to the detriment of present use for agriculture and impeded the use for multipurpose development regardless of broader regional or national interests.

7. While private enterprises may, therefore, not replace the irrigation Water Authority in future, **a contractual arrangement** between the Water Authority and a private firm to operate and maintain the irrigation infrastructure for a given time appears to have more appeal. Such arrangement could include the responsibility for conveyance of water through canals, O&M of pumping stations and other functions of the enterprise. However, also this approach is not recommended for the countries in question for some time, mainly because of general lack of entrepreneurial experience and the likely impression of farmers of being exploited by the new entrepreneurial system.

8. A middle way more acceptable to farmers and Governments appears to be the operation and maintenance of public irrigation schemes through Water User Associations (WUAs). It meets the farmers' new sense of democratic understanding of handling their own affairs and releases Governments from at least their O&M responsibilities and thus the headache of daily operations. Such type of organization is well rooted in many countries with market-oriented economies and experiences indicate that distinct advantages can be expected compared with governmental schemes such as:

-. improved water conveyance and system maintenance;
-. optimal system design and construction (through farmer participation during the planning and construction stages);
-. better relations and reduction of conflicts between government officials and farmers;
-. improved collection of water charges from the farmers;
-. improved agricultural management and crop production.[31]

Organization of WUAs

9. If the decision has been taken to establish WUAs a number of points should be observed for its organization.

10. In the context of the Eastern European Land Reforms it should be clear that the previously responsible cooperatives or State farms were a type of WUAs in terms of being responsible for all irrigation and drainage matters in an area of about 2,000 ha and more and sometimes were responsible even for the water source, but with the marked drawback that the "farmers" had no voice in decision-making and were not motivated by successful water applications since there was little personal profit to be gained. Thus, the administrative and technical know-how in managing irrigation schemes outside the irrigation departments generally exists and should be utilized for the new organization.

11. **Principles and Options.** Earlier experiences with civil-law type cooperatives proved to be unsuccessful as needed measures could generally not be implemented against the will of individual property owners. Furthermore, the statutes governing contributions and membership rights were too weakly vested.

12. Changing the status of WUAs from water cooperatives into public corporations,

[31] Refer also to "Participatory Experiences in Irrigation Water Management". Proceedings of the expert consultation on Irrigation Management, Indonesia 1984. FAO Rome 1985 (p. 13-15).

the associations were assigned the appropriate sovereign powers. They had now the compulsory means for enforcement against their own members. The members are, therefore, not confronted with the State but with their own association as initiator and enforcer of compulsory measures. Since, however, the association is nothing else than the integral whole of its members, all such measures are ultimately initiated by the members themselves.

13. The associations can in theory be founded against the will of the property owners concerned. This, however, should be an exception to the rule; normally, approval by the majority of the property owners concerned is desirable and should be considered prerequisite to the founding of such an association. To this effect legislative provisions would be required.

14. Any property owner who stands to benefit from the functions of such an association is eligible for membership. In addition to such real members, public corporations and bodies corporate and individuals may also join the association (to the extent admitted by the supervisory authority). This makes it possible to extend membership not only to agricultural land owners but also to communities, etc.

15. The functions of such an association should, in general terms, concern the water and soil resources development sector, and may cover: hydraulic engineering and developmental measures; maintenance of installations; irrigation and drainage improvements.; landscape preservation and environmental protection and flood control (construction of dams, dikes, etc.);

16. The associations can carry out construction projects and/or assume responsibility for the maintenance of the respective facilities.

17. The associations are responsible for administrating themselves, e.g. they derive their organizational structure and legal competence with respect to their own members and third parties not only from public authority but also from their own legal status (public corporation).

18. The compulsory contribution depends on how much benefit the members draw from the association. Contributions to the association itself constitute so-called public charges (taxes/levies) with which the property of the individual members of the association is encumbered, i.e. if the contribution is not remitted, the property of the member could, in an extreme case, be put up at auction.

19. As long as the differences in benefit are relatively minor, a hectare rate could be applied. In the case of an irrigation association, a m^3 measure (volume received) would be advantageous.

20. The association is responsible for organizing its own management. Each association must have a president and vice-president, and the board of executives can be expanded to include additional elected members. On principle, the president and board of executives are responsible for transacting all business and representing the association, e.g. in court.

21. Whether or not the association employs full-time administrative personnel is a matter of discretion, depending on the scope and diversity of associational functions.

22. On principle, the board of executives is elected by the general assembly. If the association is too large, that is if it has too many individual members, a committee (a sort of parliament) is elected by the individual members and then interposed.

23. The parliament has the same rights and obligations as the general assembly would have had (drawing up the budget, fixing contributions, electing the board of executives and president, hiring personnel, etc.)

24. The associations are subject to governmental judicial and technical control. The government has the right to investigate the extent of agreement between the activities of the association on the one hand, and the valid and pertinent laws and technical know-how on the other. In the event that the association is found to be in violation of the law, the government can exercise its discretionary powers.

25. The organizational law pertaining to such associations allows the founding and running of associations of different size and with totally different functions. For example, one association may concern itself only with the irrigation of less than 100 ha, while the next is responsible for many thousands of hectares, mainly concerning itself with the implementation of construction projects, maintenance facilities, overseeing "sub-associations", etc., but both may have exactly the same legal structure.

26. The associational structure allows a multi-level type of organization. The charts shown in Fig. 1 to 3 indicate the structure of an association with

-. unpaid representatives only (figure 1);
-. unpaid representatives and full-time staff, plus an advisory board (task-oriented think tank (figure 2);
-. a three-level structure (figure 3).

27. The organizational structures and management should, to the greatest possible extent, always be appropriate to the local situation. Socio-economic studies should be conducted, with special attention paid to the spheres of interest of the people who live and work in that area and to tapping the local traditional know-how with regard to water usage. Such know-how should be integrated into the associational structures in such a manner as to generate participatory interest among the potential beneficiaries. Every attempt should be made to explain the organization's envisioned structure, in this case the association system, as comprehensibly and transparently as possible to the individuals concerned (farmers).

28. Depending on the complexity of the task and the experience of the association members, it may be necessary to involve a central/umbrella association. It should have a trained management cadre with the ability to support its subordinate associations. Its concentrated managerial know-how should assume responsibility for the smooth supply of water to the sub-associations and assist their respective boards of executives in the performance of their duties, but in such a manner that they do not feel patronized. The main objective of the central association, whose initial managerial team should be recruited from outside, is to eventually replace the managerial staff with qualified executives drawn from its own member associations.

29. It is only at this stage that the direct influence of the public authorities becomes evident, but it should still be limited to advisory functions.

30. The central association also serves as a clearing point for diverse interests within the irrigation project area.

31. The association's contribution system should be in line with the services it provides. The contributions should be booked in separate accounts corresponding to the various scopes of activity, and subsidies should be pertinently appropriated. An association should be a non-profit organization.

32. The associations should, however, not strive for acceptance on the basis of anticipated subsidies, because all such interest would wane as soon as the subsidies are retrenched or discontinued. On the contrary, the benefits the farmers stand to gain for their own private interests must provide the impetus for acceptance.

33. While many of the described organizational, managerial and legal features would apply generally, the local situation will ask for some specific approaches in several areas, for example, after the dissolution of the cooperatives or State farms the only organizational structure left at the field level is the village structure. It is here where an *ad hoc* organization of irrigation water management generally initiates and it should be investigated if at that level WUAs can be successfully implemented. If - as is likely - the difficulties of combining the interests of 300 to 500 landowners under a village cannot be surmounted, smaller subgroups may have to be introduced, each covering about 40 farmers. Typically each subgroup would elect a subgroup leader who would be represented at the village water committee as outlined in Fig. 1. If the irrigation scheme encompasses several villages, the WUA leader of each village could be represented at an irrigation scheme committee from which the executive board and the president would be elected as shown in Fig. 2. Such more enlarged organization could also be the type responsible of those irrigation schemes which were previously administered by the cooperatives or State farms.

34. The rather sophisticated organizational structure for wider scope activities as shown in Fig. 3 may not be required for the immediate and medium term objective to restore order to the irrigation water management sector for some time to come.

35. For other type of WUAs the reader should also refer to FAO's Publication "Irrigation Users' Organizations in the Legislation and Administration of certain Latin American Countries", Study No. 24, 1983.

Implementation of Water User Associations

36. When implementing WUAs common issues include:

-. the need for a legal framework at two levels:
   (•) at national level (water law) and,
   (•) at local level (WUA regulations);

-. a long gestation period;

-. a major communication effort with farmers as to what is expected of them;

-. a massive training effort for both the Irrigation Department staff of different background (including visits abroad) and leaders of WUAs and their technical teams.

37. **Legal Framework.** The introduction of WUAs would need to be supported by the following legal measures[32/] :

-. legalizing WUAs in the Water Law including matters of water rights, water authority, etc.;

-. decrees to back up rights and obligations set out in the Water Law concerning water rights, water authority and establishment of WUAs; and permission of farmers' participation (through representation) in district irrigation enterprises regional management;

-. sanctioning of regulations and norms to back up, at operating level, by the new Water Law and Decrees.

38. **Gestation Period, Communication and Training.** Forming WUAs will be a difficult and tedious process of explaining each future member what an association is and then convincing him/her of the advantages of its establishment. Furthermore, there is also the problem of training in each association a small group (executive board) in operation, maintenance and administrative aspects, in such a way that they will be able to undertake these functions properly.

39. To coordinate dissemination of knowledge, a technical team should be set up which is able to assist district officials in designing and creating WUAs. The district officials in turn would inform and assist village chiefs and group leaders to form WUAs on the ground and advise on O&M procedures including contracting for water and payment of water charges. Television programmes for irrigating farmers on weekly basis would support this effort.

Water Fees

40. A WUA may be confronted with three different types of water fees as follows:

-. **Water use charge:** To pay the actual volume of water used. It would cover the O&M costs of the Water Authority.

-. **Water User Association fee:** To pay the WUA for services extended to its members, such as administrative and advisory expenses. The fee could be collected directly by WUA or by an arrangement with the Water Authority.

-. **Investment recovery charge:** For recovering investments made by the Water Authority or the WUAs to construct or rehabilitate infrastructure. It can be the repayment of a loan.

32/ Current Development and Trends in the Law and Administration of Water Resources - A Comparative State of the Art Appraisal. Journal of Environmental Law, Vol. 3, No. 1. Oxford University Press, 1991.

41. In the regulations of the law the purposes of these fees should normally be defined and in the norms of the Water Authority the procedures of calculating them should be determined. The law should also state who collects the fees and that the revenues are used for the purpose for which they are defined. In the case of non-payment of fees set by the Water Authority court action for recovery should be initiated. In the regulations it would be advantageous to delineate this procedure including methods to deal with inflationary problems. The law should state further that in all court actions the debt of a water charge has priority on other debts.

42. In designing the legal framework related to water fees it is important to keep in mind that in a farmer participated management system, the fee assessment, its collection and expending, transforms itself in one of the main commitments to manage. In the design of rules of operation the level of fiscal autonomy of the Water Authority is of fundamental importance, as much of the discussion will tend to be about the level of the operating budget, amount of revenue and results of the farming operations. For this reason the common practice of calculating a homogenized charge for the entire country should be reviewed and possibly replaced by a calculation in each district if not for each project.

Investments Needed

43. Establishing WUAs on the above principles would require investments of various nature which is generally country specific. To provide an indication, an example from Eastern Europe is presented below. The investments were designed to cover the first year of introducing WUAs on an area of about 310,000 ha, involving about 200,000 farmers. The investments were split up between local and foreign cost and amounted to about US$1.3 million or US$4.1/ha - a small sum when compared to the much higher amount of infrastructural investments made per ha and the likely benefits these investments can generate.

Item	Quantity	Cost
	No.	US$'000
A. LOCAL COST		
Incremental Staff (Water Direct.)		
. Coordinator	1)	
. Engineers	6)	13
. Translator	1)	
. Driver	1)	
Water Masters (District Irrig. Dept)	313	98
Training - Instructions		
. Water Directorate Staff	LS)	
. Village Chiefs	LS)	38
. Group Leaders	LS)	
. Television Programmes	LS	20
Sub-total		**169**
B. FOREIGN COST		
Expatriate Experts . One Master Trainer	4 man/month	50
. One WUAs Legal Expert	3 man/month	38
Vehicles (incl. 10% spares)		
. Motorcycles	78	172
. Vans	39	643
. Cars	2	30
. Fuel (Diesel and Petrol)	13 t	13
Communication Equip. (Radio)		
. One for 3,000 ha	104	20
Sub-total		**966**
Contingencies for B (15%)		145
Total Foreign Cost		**1,111**
T O T A L C O S T		**1,280**
Cost per ha		**US$4.1**

10. **FLOODWATER SPREADING** (January 1994)

Introduction

1. Use of floodwater for irrigation, groundwater augmentation, fertilization and soil accumulation has been practised for millenniums in arid regions. Worldwide degradation of watersheds during the last decades have increased the amount of floodwater, its frequency of occurrence and its sediment load. Concurrently, agricultural productivities in upper watersheds have stagnated or reduced and outmigration has become common. In search for new livelihood, floodwater spreading over desertic soils - in general over debris cones - has found increased interest as a means of developing agricultural alternatives. This paper discusses the principles of floodwater spreading and presents a case study from Iran.

Land Resources

2. In many arid or desertic countries the historic erosion and floods have generated alluvial debris cones which are used to some degree for irrigated (< 5%) and rangeland agriculture. In a country like Iran about 13 million ha constitute such type of land. The debris cones are generally expanding, particularly in recent times, due to the increased erosion from upper watersheds and higher flood levels. The active erosion of the upper watershed provides bedloads during floods, of which the coarser material (gravel) will deposit at the upper part of the debris cone. Infiltration below the river channel is high and smaller floods often do not reach the end of the cone. In such cases, all sediments remain within the river channel - thus making it progressively shallower. Typically, therefore, the depth of the river is generally less than one metre and the river easily changes its course. During floods a river delta may form with the main channel being filled first followed by the secondary channels depending upon the flood level.

3. Typically, debris cones range between 1,000 to 10,000 ha in size. Slope of a debris cone may be in the range of 0.4 to 1% with groundwater levels 8 to 20 m below surface depending upon vicinity to the river bed and degree of water use - generally for irrigation purposes. Depth of debris cones may be up to 100 m over the original plain.

4. Debris cones mirror the erodible materials of the upper watershed. Soil particles decrease with distance down the slope. Degraded (overgrazed) cones are generally covered with a layer of drifting fine sand ranging in thickness from a few mm to several cm. A structureless coarse sandy loam forms the A-horizon, 10-20 cm thick. The stony C-horizon lies generally directly under the A-horizon.

5. The original vegetation of debris cones have generally long gone. Except for the remainders of a few perennial grass species, most arid debris cones appear denuded and even desertic. Wind erosion is often prevalent, while water induced sheet erosion is minimal, due to low rainfall and limited slope. Along the major river channels, a number of brushes and seed grasses have survived. Except for a few ornamental and fruit trees in villages, no trees are left.

Water Resources

6. Degraded watersheds in mountainous regions show high rainfall/run-off coefficients. Only 5 mm/h can produce run-off as high as 40% and 10 mm/h produce major floods with run-off above 50%. Length of significant run-offs does not exceed 48 hours in most cases. Flood peaks (in m^3/s) are a function of rainfall intensity, duration, size and slope of the upper watershed. A 200 km^2 watershed may produce up to 250 m^3/s at a probability of about 50 years and 100 m^3/s once per year.

7. Run-off generated from short and intense rainfalls is generally of good quality if suspended soil material (silt and clay) is regarded as temporary. Flood waters infiltrating into the soil of flood plains or debris cones may deteriorate depending upon any saline baseflow within the aquifer.

8. Suspended soil material of a small flood (10 m^3/s from a 200 km^2 watershed) may be about 5 g/l consisting of 10% silt and 90% clay. At flows at about 100 m^3/s, 50 g/l may be suspended, thus a 100-fold increase per unit time (which indicates the exponential nature of sediment movements with increased flows).

9. Debris cones provide generally good aquifers due to their coarse soil formation and considerable depth. Typically, about 15 million m^3 can be stored for each 1,000 ha cone area. Qanats (horizontal wells) as well as dugwells were the original means to extract groundwater from the debris cones. The advent of tubewells often lowered groundwater tables below the reach of these traditional methods. Villages were abandoned as a result and new ones established in areas where tubewells could be employed. Groundwater use needed to be regulated (permits) to secure investments and social peace. In many areas no new wells or deepening of existing wells (including qanats) is being permitted.

The Value of Floodwaters

10. The loss of soil and water in the upper watershed may have a considerable value furtherdown if properly harnessed and used as follows:

-. direct use for flood irrigation of agricultural lands;
-. recharge of groundwater and prevention of salt water intrusion into the aquifer;
-. soil formation;
-. leaching of saline soils.

Benefits of Floodwater Attenuation

11. The degraded watersheds generate higher floods than previously experienced, resulting into damages as mentioned earlier. Flood attenuation through water spreading would provide the following benefits:

-. reduction of the flood peak with positive effects on flood levels downstream;
-. decreased (exponentially) riverbank erosion downstream with major benefits to reservoir siltations, river channels and any irrigation or drinking water intake structures;
-. reduction of river sedimentation load from the upper watershed.

When considering the benefits from floodwater attenuation, care should be taken not to overlook possible present economic benefits downstream of that water, which can be any of the above inherent values of floodwater including recharging of reservoirs, increased soil fertility when irrigating or environmental benefits (lakes, forest, etc.). Any proposals for floodwater spreading schemes, therefore, need careful studies as to any detrimental effects due to the intervention.

Flood Water Spreading Methods

12. Historically, flood spreading fulfilled the objective of irrigating bunded fields. In the process the fields functioned dually as infiltration ponds and sedimentation basins, accumulating the precious and highly fertile eroded soil on stony and gravelly foothills and valleys thus building productive farms in places where rainfed agriculture was impracticable. Construction of new basins further down-slope usually followed the near complete siltation of the upper ones. Although this time-proven and labour-intensive method is very effective, the prohibitive cost of its construction and operation prevents its application today. Furthermore, such systems cannot accommodate large flows; therefore, design and construction of inexpensive floodwater spreading systems of large capacity were developed.

13. The most important element in any floodwater spreading system which receives large flows from an ephemeral river, is a dual purpose conveyor-spreader channel, which transfers water to the head of the spreading area and, ideally, distributes it evenly on to the land. This channel is a long, shallow, slightly sloping stilling basin. Water is supplied to the conveyor-spreader channel by a diversion, or an inundation canal. It is imperative to realize that the conveyor-spreader channel is the only structure in the system which is connected to the river. Once filled, water will flow over the lower bank of the channel, with the resultant flow of a shallow sheet of water on a very long front. The excavated soil forms a bank on the upslope side of the channel.

14. Openings or gaps are provided in the upper bank to facilitate entrance of water into the channel during major floods when flows overtop the river channel and enter the conveyor-spreader channel also through the gaps.

15. The spillage from the conveyor-spreader channel flows over the land in a sheet whose depth and velocity depends on the flow rate, slope, infiltration capacity, ground cover, etc. The depth of water on the lower bank sill of the conveyor-spreader channel is usually 3-5 cm, rarely exceeding 10 cm. The terminal velocity of a 10-cm deep sheet of water on a 2% upper slope on denuded land seldom exceeds 60 cm/ s. At this depth and velocity, the flow is non-erosive for all practical purposes.

16. The flow of water on the land is regulated by level-silled channels which are closed at both ends. These channels, which are located at 140-250 m spacing downstream of the conveyor-spreader channel, function as described for the conveyor-spreader channel with two exceptions:

-. they receive water only through the gaps provided in their upper banks at 100-400 m intervals; thus in low flows or short duration floods they may receive no water to spread;
-. they are level along their entire lengths so they spread the water more evenly.

When floodwater reaches the end of a floodwater spreading system, it has lost most of its sediment load and can be used for further artificial recharge through construction of infiltration ponds or recharge wells or the water can be returned to the river.

The Case Study

General

17. Experiences were analyzed from Iran with the above described method. They are based on about 100 systems throughout the country. One of the systems is located in the Gareh Bygone Plain in southern Iran, 200 km east of Shiraz and represents with 150 mm rainfall/year the conditions of at least 20% of the countries low rainfall zone. The floodwater spreading system was developed with the main objective to recharge the groundwater aquifer (100 million m^3 capacity) and stabilize moving sands of the 6,000 ha debris cone by superimposing sedimentation (suspended load) from flood waters. Eight floodwater spreading sub-systems covering an area of 1,365 ha were designed and constructed during 1983 to 1986.

Design and Construction

18. A layout of the Gareh Bygone Plain floodwater spreading system is shown in Fig. 1. The 8 sub-systems are listed below with detailed information.

Name of System	Duration of Construction	Area	Length of Diversion Canal	Length of Conveyor-Spreader Channel	Level-Silled Channel Length	Tail Drain Length
		ha	………………. m ……………….			
Bishh Zard 1	Jan-Feb 1983	200	500	1,340	9,940	-
Bisheh Zard 2	Mar-June 1983	250	340	1,800	6,740	2,500
Bisheh Zard 3	Dec '83-Mar '84	25	330	400	1,000	1,000
Bisheh Zard 4	Jan-Mar 1984	25	300	200	920	-
Rahim Abad 1	Jan-June 1984	200	200	2,500	7,900	2,600
Rahim Abad 2 + 3 [a/]	May 1983-Feb 1987	300	1,540	540/1,950	4,340/6,450	1,780
Tchah Qootch 1	Nov 1985-Feb 1987	365	500	7,000	14,350	-
TOTAL		**1,365**	**3,710**	**15,730**	**51,640**	**7,880**

[a/] The RA2 diversion canal supplies two systems through specially designed weir and drops.

19. The Bisheh Zard River supplies floodwater to 7 systems and the Tchah Qootch River to only one. Since each system is designed to fit the lay of the land, the length of the conveyor spreader channels and the level-silled channels, as well as the number of the latter, differ considerably among the systems. Except for the systems Rahim Abad 2 and Rahim Abad 3, which are fed by a single diversion canal, each system is supplied by an individually designed diversion canal. Furthermore, the possibility of supplying the lower lying systems with the surcharge of the upper ones has eliminated five of the tail drains. Only one tail drain on each side of the Bisheh Zard River floodwater returns the surcharge to the river. The return flow of the Tchah Qootch River system is discharged into the Bisheh Zard River

through its left bank tail drain. Design details of the systems include the following:

-. the intake structures were protected by groins, made of gabions and spaced to allow 50 l/s/ha to pass into each sub-system. The river bed and its banks were protected by groundweirs, again made of gabions, having a triangular cross-section of 0.7 m upstream thickness tapering out to zero after 3 m downstream. Width was about 28 m and the weir sill was placed 5 cm above the conveyor spreader channel bed entrance;

-. the slope of the conveyor-spreader channels was set at 0.0003 for about 85% of their lengths; the slope of the final 15% was decreased gradually to zero. This ensured a more uniform spreading along the entire length of each channel during high flows, and priority flooding at the end of the canal system during low flows;

-. vertical canal intervals of 1.10 m and 0.75 m were adopted on slopes of 0.5-0.7% and 0.3-0.5% respectively, resulting in the spacing of 140-250 m for the level silled channels;

-. construction of end banks perpendicular to the channels confined floodwaters to the spreading areas, thus preventing both uncontrolled flooding of the adjacent lands and return of the water to the river in unsuitable places;

-. construction of tail drains ensured safe return of the surcharges to the Bisheh Zard River;

-. bulldozers (125 hp) were employed in constructing the water conveyance and spreading systems. Furthermore, a rubber-tyred loader was used to construct the level-silled channels in the dry, drifting sands because the bulldozer tracks would have peeled the protective mat of the grass *Carex stenophylla* off the soil surface, thus exposing the sand substratum to the hazards of wind and water erosion;

-. the very severe erosion which occurred during the first floodwater spreading event in and around the gaps, necessitated construction of specially designed chutes and drops in the gaps. The level of the sills of these structures should be raised with increasing depth of siltation in the upstream basin.

Results

20. There were 22 floods during 1983 to 1988 allowing a total diversion of about 38 million m^3 as shown below.

Date		Estimated Peak Flow	Duration	Volume of Diversion
Year	**Month**	**m^3/s**	**hours**	**Million m^3**
1983	January 19-20	48	24	0.07
	March 6	30	19	0.07
1984	February 27	70	20	1.10
	March 21	40	5	0.40
	March 22-23	50	34	1.80
	March 24-26	60	48	2.60
	March 28-31	60	40	2.10
1985	January 4	30	17	0.92
	January 20-24	40	20	1.20
	May 12	30	2	0.10
	December 19-20	70	26	3.10
1986	March 8	80	26	3.20
	July 26	100	13	1.00
	Nov. 30 - Dec. 1	200	24	3.90
	December 2-3	300	26	7.80
	December 4-6	130	34	2.40
	December 6-7	100	8	0.60
1987	August 18	20	2	0.07
1988	January 18	100	15	1.90
	February 23-25	30	50	2.70
TOTAL				**38.13**

21. The number of wells increased from 16 to 58 during the above period, irrigating an additional 492 ha and allowed augmentation of water supply to existing 514 ha (in 1993, the number of wells have increased to 94). In addition, about 30,000 trees *(Eucalyptus camaldulensis)* were planted as windbreaks along canals and at 3 x 3 m spacings over about 70 ha. Some of these trees are now about 18 m high. The annual vegetative dry matter production increased from about 35 kg/ha to about 500 kg/ha within the floodwater spreading area, which supports about 3,500 sheep and goats for about 45 days per year.

22. Sedimentation on the upper reaches of the system has reached 50 cm of fertile soil in 1993, which reduces in depth toward the lower areas. About 200,000 m^3 have been deposited annually.

23. The system can absorb up to about 100 m^3/s or about 73 l/s/ha (higher than designed), thus reducing any flood by up to that amount. A major flood in 1986 which left the Fasa Basin (to which the Gareh Bygone Plain drains) with 2,000 m^3/s, killed 424 people and

damaged about US$8 million worth of property. Without the flood spreading scheme, the flow would have been 2,100 m^3/s and damages exponentially higher. If more flood spreading schemes would have existed on the other debris cones contributing to the Fasa Basin run-off, the disaster could have been largely avoided.

24. Another pleasant by-product of the scheme was the inward migration into the area. Irrigation water availability has encouraged many absentee farmers to return to the Gareh Bygone Plain over the years. Moreover, seasonal farm labourers have found well-paying jobs as irrigators, farm machinery operators and the like.

Cost

25. The overall cost of the system in 1993 prices were about US$450,000 or US$332/ha, as itemized below.

Item	**Unit Cost**	**Cost per ha**
	………………. US$ ……………….	
Design and supervision	70/h	28
Surveying	28/h	14
Bulldozer (125 hp)	50/h	80
Structures	$142/m^3$	150
Tree planting	2/tree	60
TOTAL		**332**

26. Operation and maintenance (O&M) of the station in 1993 has costed about US$13,600 or US$10/ha.

Development Potential

27. Of the 13 million ha of debris cones in Iran, more than 20% are located in rainfall areas with at least 150 mm of precipitation, as mentioned earlier. Thus, about 2.6 million ha appear to be available for a type of development as implemented in the Gareh Bygone Plain.

28. A development at such scale would call for private initiative rather than for governmental services, particularly regarding 0&M of such schemes. Groups of individuals or entrepreneurs would have to become involved financially as well as organizationally. As virtually all lands of the debris cones are declared State property (rangeland), mechanism would have to be found to lease the areas for long term (such as 99-year leases) to potential investors. In many countries such type of development would be organized through Land and Water User Associations (LWUAs), who act legally as a person and thus would be eligible to borrow from commercial banks for the required investments. Such associations are normally governed by law and conduct their business by following strict rules and regulations. Since their activities would be of public interest by generating benefits to the economy (flood protection, reduced reservoir sedimentation, etc.), financial State support

may be considered on a case-by-case basis. No such association exists in Iran at present in any field and considerable effort would be required for its establishment and maintenance.

29. Development through entrepreneurs would be easier to organize - again based on long-term leases - however, its social acceptability (the rangeland is *de facto* owned by the local population and nomads) would be more difficult, particularly if the benefits (such as increased water supply, improved rangeland, flood reduction) would need to be sold to customers including the State in order to generate a profit.

A Possible 5-year Programme

30. Subject to successful organizational arrangements for implementation (Associations, individuals or State), an initial programme covering about 120,000 ha - or about 90 debris cones - over a period of 5 years has ben proposed at a cost of US$30 million. Together with O&M of the schemes over 5 years (US$10/ha/year), incremental staff, funds for training and miscellaneous about US$10 million would be needed resulting in a total investment of tentatively US$40 million.

31. The investments would allow diversion of about 800 million m^3 of water per year and retain about 20 million m^3 of sediment annually on the debris cones. Irrigated areas should potentially increase by about 50,000 ha through private groundwater development. Priority of development should be given to watersheds feeding existing reservoirs after careful water balance studies have been made.

Environmental Considerations

32. The degrading watersheds have released increasing amounts of water to low lands over the years to which the environment adapted itself. Flood spreading schemes would reduce this amount, requiring careful studies of its effect downstream. On the debris cones itself the development would create a pleasant environment for men and conducive for flora and fauna of an oasic type. The use of stored groundwater for irrigation would permit increased human activity in the areas, revert migration and improve land quality in a now generally hostile and fragile environment.

(Editor's Note: regrettably the Figure 1: Typical Layout of Floodwater Spreading System (1365 ha) which appears on p. 86 of the printed paper could not be reproduced in complete in this PDF edition of the document.)

11. SALINITY CONTROL (September 1992)

Introduction

1. All irrigation waters carry a certain amount of dissolved solids - even when rated of good quality in terms of salinity (i.e. < 0.7 dS/m or < 0.5 g/l of dissolved solids). Consequently, evapotranspiration of the irrigation water leaves solids behind in crystallized forms (salts). This salt affects water availability to plants, as its affinity for water is in competition with that of the plant roots; if the salt concentration in the soil solution is high enough, it will prohibit sufficient water uptake with known adverse consequences to the plant. The salt brought in by irrigation water to the root zone needs therefore to be removed to a certain acceptable limit (salinity control), which is generally achieved through leaching-out of salts and their drainage out of the area.

2. Many desert civilizations have disappeared in the past when this type of salinity control was not practised. Those that did not were subject to natural drainage mechanisms often together with periodic floods that washed the accumulated salts at the soil surface away.

3. The introduction of irrigation practices in modern days still faces the same challenges when natural drainage is inhibited by low soil permeability, topography, lack of water availability for leaching purposes or lack of possibilities to discharge the drainage water. In such cases, the chronology of events is generally as follows: after commencement of irrigation the groundwater level rises into the upper soil layers after some time (perhaps within a decade) which inhibits leaching of salts below the root zone (along with the excess irrigation water). Evaporation of water from the high groundwater - through soil pores and cracks - transports salts to the soil surface, where it crystallizes and becomes visible (white). Adding irrigation water to the soil dissolves the salts again and moves them temporarily out of the upper soil layers, sometimes also to neighbouring unirrigated fields through horizontal movements. The suppressed and the newly added salts from the last irrigation return to the upper soil layers after the irrigation ceases. To control the salts, more irrigation water is supplied than necessary at ever shorter intervals due to an increasingly higher salt concentration. As a consequence the soil also becomes waterlogged and the amount of salt added increases even more rapidly. At this point agriculture is in its last phase and becomes unprofitable because of seriously declining yields.

4. Relief could come - provided soil conditions are favourable - from groundwater development programmes and in particular from the construction of a proper drainage system. The former provides merely a temporarily relief while the latter offers a definite halt to the salination process but is rather costly.

5. Groundwater development programmes to control salinity involve a process whereby the deeper lying, relatively good quality groundwater is used for supplementary irrigation after being pumped to the surface. The excess irrigation water together with the leached salt percolates from the upper soil stratum into the space created by the groundwater abstruction and thus out of the rootzone. As the original water source (the one that delivered the salt in the first place) will continue to provide part of the irrigation water, the relief is only temporary as the salt will eventually (depending on the circumstances such as the water quality, climate and rate of supplementary irrigation) contribute to a deterioration of the groundwater quality and thus the irrigation water. In some cases the groundwater option is

considered a short term solution, while in others, depending on the costs of the drainage option, a sound financial decision. However, it is not a permanent solution.

6. In contrast, the construction of a proper drainage system seems to be the answer to the salinity control question depending on the investment cost involved and the benefits derived therefrom. The amount of investments required for a proper drainage system varies and depends upon the type of soil involved, the length of conveyance for the drained water, the need for pumping, the drainage disposal system and finally the cost of the land required on which to build the system.

7. To illustrate the issues, costs and benefits involved in a typical drainage project for salinity control, a drainage project profile of eastern Iran is presented below.

The Case Study

8. The area under consideration (Map 1) has been under irrigation for thousands of years. Water was in abundance. As also land had been no constraint in the past, salinated lands were abandoned and new lands irrigated somewhere else. Soil salinity of the abandoned lands had been eventually removed by recurrent floods, some rainfall (50 mm/year) and some limited natural drainage. Once the salinity had disappeared, the land was then recultivated whenever necessary and the cycle repeated itself.

9. During the last three decades changes occurred that adversely affected the balance of the system. For one, population increased rapidly and more land was put under irrigation, thus reducing the opportunity to shift to other areas. At the same time upstream developments and flood protection measures reduced the flood events, thus the washing away of salts from the soil surface. Furthermore reservoirs were introduced within the system to enable a certain degree of summer irrigation which again added more salt to the lands even though the water quality of the river water was considered of good quality for irrigation purposes (about 0.5 g/l of dissolved solids). As the water use efficiency was only about 20%, due to the losses from the traditional irrigation distribution network and to the need to suppress salts, about 30,000 m^3/ha/year of irrigation water was delivered into the system bringing along about 15 tons/ha/year of salts, or 210,000 tons/year within the project area of 14,100 ha. Very little of this amount was removed by natural drainage (no slope) or by floods. Farmers were scooping salts off their fields with tractor driven implements prior to seeding. This resulted in loss of top soil and high additional cost, leading to an unsustainable situation. Wheat yields decreased and are at present about 0.7 tons/ha, while its potential is about 3 tons/ha. It was clear that agriculture was threatened with extinction.

10. So far the accumulated salts in the project area have been estimated to be over one million tons. Groundwater development was not possible, as the groundwater itself was highly saline. The solution was seen in the introduction of a drainage system that would drain the salts out of the project area. Leaching tests revealed that the salinity can be removed from the alluvial soil within two years, i.e. about 70% of the salts could be removed in the first year followed by the remainder in the second year. The drainage rate was found to be between 2.0-2.5 mm/day.

11. To save land a subsurface pipe drainage system was considered. Calculations revealed that lateral pipes protected with a gravel filter and placed on average at 2 m depth would require a spacing of 100 m. These findings were in line with results of two existing

pilot systems in the vicinity of the project area. The downwards sloping lateral pipes (PVC, diam. 10 cm) would discharge into collector pipes made of concrete (diam. 20-50 cm) spaced 500 to 1,000 m apart and placed on average 3 m below ground. The collectors would be connected to a tertiary open canal system spaced 1,500 m apart from where the drainage water would be flowing via secondary canals towards a main outfall canal. The low slope of the area required pumping and a total pumping power requirement of 800 hp needed to be installed in 4 pumping stations. For ecological reasons the drainage water needed to be conveyed away from a nearby fresh water Lagoon (Map 1) toward a drainage water disposal site (evaporation pond) taking the form of a 5,800 ha large depression, 20 km away from the project area in a desertic region. The evaporation capacity of the pond has been estimated at above the amount of drainage water expected, i.e. 60 Mm^3/year. To ensure no escape of salt from the evaporation pond a 12 km long flood protection embankment would have to be constructed along one side (Map 1). As the evaporation pond would be more than 3 m deeper (3,000 mm) than the surrounding lands its salt accumulation capacity would be beyond the project's life expectancy (there would be 9 mm from leaching the accumulated 1 million tons and only 1.2 mm would be added yearly representing the 210,000 tons). The deposited salt would be largely dissolved at high concentration (evaporation reduces with rising salt concentration) which would protect the salt from becoming airborne - except for some fringe areas which may occasionally become dry. However the prevailing winds would carry salts away from habitations or agricultural lands into the desert so that the potential hazard would be very limited.

12. With the salt balance corrected, irrigation aspects would become the next physical constraint. Even though water use efficiencies of presently about 20% would increase as the need to suppress salts would decrease after the provision of proper drainage, further improvement in water use efficiencies would be advantageous considering an overall water shortage in neighbouring irrigation areas. A reasonable water use efficiency of about 35% was thus envisaged. This was to be obtained through investments into the existing irrigation infrastructure and its improved operation.

13. Some of the rehabilitation of the existing irrigation infrastructure would also be needed in areas where agriculture had been abandoned due to salinisation. In addition, some adjustment work on the irrigation network would be required as a result of the construction of the drainage network which would cross a considerable number of irrigation channels.

14. The above works would need to be supported with agricultural support activities in order to exploit the production opportunities created. This would include support of the Extension Service - particularly in water management matters - support of the existing Agricultural Research Station (soil reclamation, salinity control, leaching requirements, crop response to different salinity levels, etc.), planting windbreaks and stabilizing dunes.

Duration and Phasing

15. The construction of the main canal together with the pumping stations was estimated to require about 2 years. Thereafter the open canal system and the subsurface network, as well as the irrigation component, could be installed over a span of 4 years together with the smaller components, thus leading to a 6 year project. This time span was also considered adequate for training of the Extension Services and farmers in improved agricultural and water management matters.

Organization

16. Implementation of the individual components was planned to be the responsibility of a Project Implementation Unit through which contractors would be engaged. O&M of the drainage system - including the subsurface pipes - would be done by the already existing water management authority. O&M for the project implementation period was considered to be part of the project cost.

Project Cost

17. The above works and activities would require investments of about US$32 million or US$2,300/ha as detailed below:

	Unit	Unit Cost US$'000	Quantities	Base Cost US$'000
A. Drainage				
1. Engineering	lsum			1,580
2. Land Acquisition	ha	2.0	300	600
3. Construction				
a) Outfall canal	km	80.0	20	1,600
b) Open canals	ha	0.4	15,000[a/]	6,000
c) Pumping Stations	No	280.0	4	1,120
d) Structures	ha	0.06	15,000	900
e) Embankment for e-pond	km	60.0	12	720
f) Subsurface drainage	ha	0.76	15,000	11,400
g) Bunding for leaching	ha	0.06	4,200	252
Sub-total Construction				21,992
4. Equipment and Vehicles	lsum			1,140
5. Recurrent Cost for O&M	lsum			480
Sub-total Drainage				25,792
B. Irrigation Improvement				2,260
C. Agricultural Support				918
D. Project Implementation Unit				530
Total				**29,500**
+ 10% physical contingencies				2,950
GRAND TOTAL				**32,450 or US$2,301/ha**

[a/] Gross area.

Benefits

18. The drainage improvement and the supporting measures were expected to allow crop production to expand considerably compared to the present situation. This would result

from five factors:

(i) reversal of the declining trend of the cultivable area due to reclamation of saline lands;

(ii) reversal of the decreasing crop yield trend due to the reduction of soil salinity; yields of most crops would at least double;

(iii) reversal of the decreasing cropping intensity;

(iv) a shift to a higher-value cropping pattern.

19. In addition, about 50 Mm^3 of irrigation water would be saved annually which could be used for crop production elsewhere. The table below compares the present with projected yields.

Crop	**Present t/ha**	**Projected t/ha**
WINTER		
Wheat	0.7	3.1
Barley	0.8	2.6
Alfalfa	5.0 dry	12.0 dry
Grapes	6	12
SUMMER		
Alfalfa	5 dry	12 dry
Clover	4 dry	7 dry
Sorghum	25 wet	40 wet
Melons	15	25

20. A summary of the envisaged cropping pattern development is as follows:

Crop	Present ha	Projected ha
WINTER		
Wheat	7,000	6,200
Barley	966	2,330
Alfalfa	1,050	1,400
Winter Vegetables	44	470
Grapes	42	930
SUMMER		
Alfalfa	1,050	1,400
Clover	280	310
Sorghum	235	310
Melons	427	1,860
Summer Vegetables	76	310

21. A production estimate at full development is shown below (note the further decrease in production in the "without project" case):

Crop	Present	Without Project	With Project	Incremental Production
	……………………. '000 t/year…………………….			
Wheat	4.9	2.4	18.4	16.0
Barley	0.8	0.4	5.9	5.5
Alfalfa - dry	5.3	2.6	16.2	13.6
Clover - dry	1.1	0.6	2.1	1.5
Sorghum - wet	5.9	5.9	12.2	6.3
Melons	6.4	6.4	45.8	39.4
Grapes	2.5	1.2	10.9	9.7

22. Considering the above incremental production an economic rate of return of 14% was calculated. Thus the project was considered financially attractive besides for socio-economic and even strategic reasons.

12. LABOUR COSTS IN MODERN IRRIGATION TECHNOLOGY (September 1995)

Introduction

1. In developing countries it is often taken for granted that advancing irrigation development would imply the introduction of modern irrigation technology such as the travelling gun or localized (micro) irrigation methods (drips and mini-sprinklers). This is likely to be a misconception as modern systems have generally been developed in high labour cost countries to merely compensate for high labour cost to operate the systems, - including cost of management - or for application in very special circumstances.[33] The word "modern" in this case is thus misleading as its meaning - an improvement of the technology, i.e. efficient distribution of water at low cost, has not necessarily occurred. Instead "modern" in this case means "labour saving". To circumvent this argument it has been claimed in many cases that labour in developing countries for agriculture is just not available and therefore labour saving equipment is needed. This, however, may not be well founded as the scarcity may only be a reflection of low wages, while there would be an ample labour supply once significantly higher salaries would be offered. This paper attempts to demonstrate that labour cost should be a main consideration in an analysis to determine what type of "modern" irrigation technology to apply.

Time-Labour Requirements

2. Before any analysis can be made to determine the most appropriate irrigation technology, time-labour studies should be undertaken for the technology under consideration, as labour requirements vary with the irrigation technology applied. Table 1 below summarizes labour requirements for typical surface, sprinkler and localized irrigation systems. The data were assembled from various publications on time-labour studies. As can be seen, labour requirements for the different irrigation systems vary from 0.4 to about 10 hr/ha/application or by a factor of 25. The labour requirements include time needed to prepare the field for irrigation as well as to install and dismantle equipment for possible storage during the off-season.

33 Use in greenhouses, for use with saline water, etc.

Table 1. Time-Labour-Requirements of Various Irrigation Technologies

Irrigation Technology	Labour Requirement[a/]	
	ha/labourer	hr/ha/75 mm application
Surface Irrigation		
. Basin	11	9.7
. Border Strip	12	8.9
. Furrow	14	7.6
Sprinkler Irrigation		
. Portable System	30	3.6
. Permanent Set	250+	0.4
. Side-Roll System - Power Driven	50	2.1
. Travelling Gun	60	1.8
. Linear Moving	250+	0.4
. Centre Pivot	250+	0.4
Localized Irrigation		
. Drip	40	2.7
. Mini Sprinkler	50	2.1

[a/] Data on ha/labourer were converted for comparison reasons to hr/ha/75 mm application and vice versa using 110 days irrigation season at 8 hrs/day and 7 applications/season. Thus, time available for a season: 110 days x 8 hrs/day for 6 days/week = 750 hrs per season. Example for basin irrigation: for 11 ha = 750 hrs. For 1 ha = 750/11 = 68 hr. For 1 application = 68 hr/7 = 9.7 hr/ha.

3. The above data should be applied with caution as variations in labour requirements may be considerable within each technology. For example the labour requirements of a portable sprinkler system already installed in the field may depend upon factors such as:

(i) Distance moved for each lateral setting;

(ii) Weight, length and size of lateral pipe;

(iii) Manner of coupling and uncoupling pipe; and

(iv) Height and thickness of stand of crop grown. Also planting patterns of crop.

Similar factors would apply when analyzing the labour requirements for other irrigation systems. Evidently, time-labour studies for each technology are indispensable for final analysis.

Other Cost Elements

4. Any cost comparison between labour intensive and labour saving methods would also need to take into account the technology's investment costs, life expectancy, power requirement, technical performance and maintenance cost.

5. Table 2 below indicates cost of on-farm irrigation systems based on data of one country (South Africa) and indicates the life expectancy of the systems, their power requirements, typical on-farm water distribution efficiencies and cost of annual maintenance.

Table 2. Data Comparison of Several Irrigation Systems in Use in South Africa

Irrigation Technology	On-Farm Investment Cost[a/] (US$/ha)	Life Expectancy (Years)	Power Requirement for 75 mm irrigation (kWh/ha)	Typical On-Farm Water Distribution	
				Efficiency (%)	Annual Maintenance (% of Investment Cost)
Surface Irrigation					
. Basin	700	20	0	75	1
. Border Strip	840	15	0	65	1
. Furrow	420	10	0	70	1
Sprinkler Irrigation					
. Portable System	900	12	150	75	2
. Permanent Set	2,700	15	140	75	1
. Side Roll-Power Driven	1,100	12	160	75	2
. Travelling Gun	1,200	10	375	65	6
. Linear Moving	2,500	15	190	80	6
. Centre Pivot	1,900	15	370	70	5
Localized Irrigation					
. Drip	2,900	10	45	90	3
. Mini Sprinkler	1,900	10	60	85	3

[a/] Including pumps and filters where applicable. Costs are updated to 1995 prices.

Source: Irrigation Systems - A Practical Guide for Farmers - Eskom, South Africa, 1989.

Labour Cost Analysis

6. In order to demonstrate the cost of labour as a function of irrigation technology, four irrigation methods were analysed, i.e. furrow, a portable sprinkler irrigation system, the travelling gun and drip irrigation. Possible differences in yields obtainable with each methodology were ignored simply because no consistent data were found. Still enormous crop yields are reported for some technologies - particularly with localised irrigation, including drip. These results are related, however, typically to desert agriculture using saline water compared to conventional methods under the same conditions. In general, well managed surface or sprinkler systems using good quality water on clay loam soils have produced similar yields to drip systems under the same conditions and with only slightly higher water consumption.

7. **Furrow irrigation** is the most widely used method of surface irrigation for row crops. Its advantage lies in low capital investment cost, no on-farm power requirement and

fairly good water use efficiency (about 70%). Its disadvantage lies in its high labour requirement (only 14 ha per labourer, Table 1), the need of a uniform minimum slope (which may imply land levelling costs) and restrictions to row crops.

8. **Portable sprinkler systems** are also relatively labour intensive as the pipes need repositioning from each area irrigated to the next. Before it can be moved, the pump must be stopped, the laterals disconnected and drained. After the move the laterals need to be reconnected and the pump restarted. Pressure requirements are in the medium range between 3 to 4 atm which requires energy cost of about US$ 15 for each 75 mm of application if cost/kWh is US$ 0.10. For each position a strip of 14 to 18 m is irrigated. The water distribution efficiency of these systems is about 75% and thus slightly higher than with furrow systems. Capital costs are about US$ 900/ha for the on-farm part of the system. About 30 ha can be operated by one labourer. Life expectancy of the equipment is about 12 years.

9. **The travelling gun** consists of one large sprinkler mounted on a wheeled trolley. The unit is pulled slowly through the crop and parallel strips of 50 to 60 m wide are irrigated. The advantages of the travelling gun includes the ease of storage (compact) and transport (mounted generally on trailers) compared with other mobile pressure systems. It can be installed and connected to the water source by one person (and a tractor) and can be left unattended until one irrigation application is completed (say, after 6 hours). Disadvantages include its high on-farm capital cost (about US$ 1,200/ha, which is due largely to the high labour cost of the manufacturing country), high energy cost (as total water pressure needs to be between 7 to 10 atm, which is equivalent to 70 to 100 m lift), the need for hydrants along the field boundary, relatively low water distribution efficiency (about 65%) particularly under windy conditions, large water drops which may be detrimental to young plants and may seal the soil surface in some soils, high cost of spare parts and difficulties in their procurement if these need to be imported - particularly if fully automatic equipment has been chosen. Cost of energy for pumping is about US$ 38 for one application of 75 mm if the cost of 1 kWh is US$ 0.10. Life expectancy of the equipment is about 10 years.

10. **Drip irrigation** systems usually consist of a polyethylene pipe with emitters spaced 0.6 m apart, delivering water at a rate of 2 to 4 l/hr. Pipes are usually permanently located 1 to 2 m apart and operating pressure requirements are about 1 atm. The advantages of drip irrigation include high water use efficiency (about 90%), potential for use of saline water, low pressure requirements, less weed growth and reduction in labour cost. Disadvantages include the high capital cost (about US$ 2,900/ha), need for pumping, sensitivity to clogging, salinity build-up and limited root development.

Cost of Irrigation

11. Comparing the four irrigation technologies the following variables are taken into account: depreciation over the respective life expectancy as shown in Table 2, interest at 8%, energy cost at US$ 0.10/kWh, repair and maintenance of the systems (Table 2) and labour cost as shown in Table 1. Costs of water and taxes are ignored in the analysis. The results are shown in Table 3 for two levels of labour cost and graphically in Figure 1 for all labour cost between US$ 0.25/hr to US$ 10/hr.

Table 3. Cost per Application of 75 mm/ha

Item		Furrow	Portable Sprinkler	Travelling Gun	Drip
		……………… (US$/75 mm) ………………			
Depreciation[a/]		6.0	10.7	17.1	41.4
Interest (8%)[b/]		2.4	5.1	6.9	16.6
Energy[c/]		0	15.0	35.7	3.2
Repair and Maintenance[d/]		0.6	2.6	10.3	12.4
Sub-total		9.0	33.4	70.0	73.6
Labour	at US$ 1/hr	7.6	3.6	1.8	2.7
	at US$ 10/hr	76.0	36.0	18.0	27.0
Total at Labour US$ 1/hr		**16.6**	**37.0**	**71.8**	**76.3**
Total at Labour US$ 10/hr		**85.0**	**69.4**	**88.0**	**100.6**

[a/] Based on 7 applications/year (or 525 mm). Example: US$ $\frac{420}{10} \times \frac{1}{7} = 6$.

[b/] Example: US$ $\frac{420 \times 8\%}{2 \times 7} = 2.4$

[c/] Example: 150 kWh/ha for 75 mm at US$ 0.10/kWh = US$ 15.

[d/] Example: 1%/year of US$ 420: by 7 applications = US$ 0.6.

12. As can be seen from Figure 1 the cost of furrow irrigation is relatively sensitive to labour cost, while that of the travelling gun is rather insensitive. Under the given assumptions the use of furrows would be cheaper compared to a portable sprinkler system until labour costs would exceed about US$ 6.0/hr. Compared to the travelling gun, labour cost would have to exceed US$ 10.0/hr before the travelling gun would be justified compared to a furrow system. Comparing the portable sprinkler systems with that of the travelling gun indicates that the use of portable sprinkler system is always cheaper than using the travelling gun within the range of labour cost investigated. The extensive use of the travelling gun in industrialized countries may thus be explained by: (a) labour cost exceeding US$ 10/hr (which is the case in many countries); and (b) the impracticability to employ temporary labour for the portable system (two labourers would be required in general for a short time daily), whereas the travelling gun can be handled by one person - usually the farmer himself.

Conclusion

13. It should be noted that the analysis presented in this paper used average cost data from South Africa, and ignored water cost, taxes and possible differences in potential production. The conclusion of the analysis should be regarded therefore only as indicative. Its methodology, however, is applicable for deciding which technology to apply under a particular situation. Nevertheless, it is quite clear from this analysis that the general assumption of modern technology being better - technically and economically - than existing or older technologies is questionable. In each case the choice of which technology to introduce needs to be assessed under the local circumstances.

13. COST OF SOLAR PUMPING IN THE SAHEL (January 1996)

Introduction

1. Harnessing the free energy from solar radiation at a cost below that provided from conventional energy carriers has been the objective ever since the first solar modules were built in the 1950s. Today, applications are common in daily life, but less so for providing energy for pumping of water, even though solar pumps have been manufactured for 2 decades and a variety of different types can be bought off the shelf.

2. High levels of solar energy and high water requirements generally go together for domestic water consumption and irrigation water needs and thus pumping. This is true also for the Sahel where average daily incoming radiation at ground level is about 5,500Wh/m^2. A recently completed World Bank assisted project in Sudan therefore included solar powered pumping of domestic water on a pilot basis. The collected data allow the comparison of cost of pumping between solar, hand and diesel operated pumps. While the project component was designed for pumping of domestic water from relative deep groundwater levels, the collected data allow also cost calculations for irrigation water from shallower depth.

Cost of Water for Domestic Water Supply

3. Production cost has to take all investment and operational costs into account. In addition, savings have to be made throughout the life of the equipment in order to allow its replacement after its useful life has expired (depreciation). Furthermore, as the invested capital does not earn interest elsewhere (opportunity cost) also this has to be accounted for as part of the production cost.

4. The basic data in Table 1 represent the average conditions in the project area, the average prices for wells, pumps, etc. and specific technical information of the different pumps. Economic life of the equipment has been estimated from experience and interest on capital has been assumed to be 10%.

Table 1. Basic Data

Item	Hand-pumps	Diesel Powered Wateryards	Solar	
			Water Points	Wateryards
Installation Cost - Total (US$)	(3,000)	(44,000)[34]	(10,500)	(22,000)
- Well 6_", 150 m (US$)		16,000		
- Well 4", 100 m (US$)				5,000
- Well 4", 55 m (US$)	2,300		2,300	
- Pump & diesel engine (US$)		12,000		
- Pump (US$)	700			
- Modules & sub. pump (US$)			7,200	11,000
- Auxiliaries (US$)		16,000		6,000
. reservoir		_		_
. pump-house/solar yard		_	_	_
. operator house		_		_
. ticket room		_		_
. taps and cattle yard		_		_
Depth to water table (m)	35	60	35	60
Horsepower used (hp)	0.1	7	0.3	0.75
Economic life (years)	15	15	12	15
Time operated/year (hrs)	1,600	2,000	1,500	1,500
Pump capacity (m^3/hr)	0.4	12	0.6	1.3
Annual pumping (m^3)	640	24,000	1,150	2,800
Fuel consumption (l/hr)	0	1.4	0	0
Food consumption for pumping (US$/year)	22[35/]			
Cost of diesel (US$/l)	0	0.28	0	0
Interest on capital (%)	10	10	10	10

34 Submersible or turbine pump.

35/ Extra food requirement for pumping is taken as 1 kg/day of sorghum equivalent at a cost of US$ 0.05/day or US$ 22/year (ref. FAO - Irrigation Water Management Brief No. 66).

5. Table 2 calculates the fixed cost of the investment, the variable cost and staff cost for operation as follows:

Table 2. Cost Calculations for Pumping

Item	Hand-pumps	Diesel Powered Wateryards	Solar	
			Water Points	Wateryards
	.... (US$/year)			
A. Fixed Cost				
Depreciation:				
- Hand-pump: US$ 3,000/15 years	200			
- Diesel: US$ 44,000/15 years		2,933		
- Solar water points: US$ 10,500/12 years			875	
- Solar wateryards: US$ 22,000/15 years				1,466
Interest:				
- Hand-pump: US$ 3,000 * 0.10/2	150			
- Diesel: US$ 44,000 * 0.10/2		2,200		
- Solar water points: US$ 10,500 * 0.10/2			525	
- Solar wateryards: US$ 22,000 * 0.10/2				1,100
Sub-total:	**350**	**5,133**	**1,400**	**2,566**
B. Variable Cost				
Fuel:				
- Food	22			
- Diesel: 2,000 hr * 1.4 * 0.28		784	0	0
Lubricants				
- Diesel: 10% of fuel	0	78	0	0
Repair and Maintenance				
- Hand-pump	50			
- Diesel		500		
- Solar water points			120	
- Solar wateryards				200
Sub-total:	**72**	**1,362**	**120**	**200**
C. Staff Cost				
Operator	0	180		
Guard	0	140	140	140
Sub-total:	**0**	**320**	**140**	**140**
Total Cost:	**422**	**6,815**	**1,660**	**2,906**
Cost/m^3 Pumped:	**0.66**	**0.28**	**1.44**	**1.04**

6. The cost comparison indicates that diesel powered wateryards are the cheapest means of supplying water followed by hand pumps, solar wateryards and solar water points. Water pumped from solar wateryards cost 3.7 times more than water from diesel powered pumps, and water from solar powered water points is still 2.1 times more costly then water pumped by hand - even considering extra food requirements for pumping. The main reason for the disadvantage of solar pumping is its high initial cost per unit power output which is reflected in low pumping rates for each dollar invested.

Cost of Water for Irrigation

7. With cost of water as high as shown above irrigation would not be profitable for most crops in Sudan. For example, it takes about 500 l of irrigation water to produce 1kg of sorghum which costs US$0.52 in water input alone to produce a grain value of only US$0.05; or about 200 l of irrigation water to produce 1kg of tomatoes which costs US$0.21 in water input to produce a value of only US$0.15. If one considers that the water cost is only a fraction of the total input to produce a crop, say up to 30% of the final product's cost, the situation deteriorates further. In the case of tomatoes and an 80% efficient water distribution (hose-type irrigation), and a 10% profit on the product, cost of water/m^3 should not exceed US$0.15 x 0.3 x 0.8 x 0.9 = 0.03/m^3 or US$150/ha when considering 500mm of irrigation. In order to derive at such low pumping cost, the heights of pumping would have to be considerably lower than those shown in Table 1.

8. Using the underlying unit cost of the above data, cost of solar pumped water has been calculated for heights of 8m (groundwater) and 3m (open surface) as shown in Table 3 and 4 below. The cost of water pumped with diesel engines has purposely not been determined under the assumption that the solar pump would operate in a remote area and diesel fuel would thus not be available.

Table 3. Basic Data

Item	Solar	
	8m Lift	3m Lift
Installation Cost - Total (US$)	(12,350)	(10,050)
- Well 4", 20m, (US$)	1,300	
- Modules and submersible-pump	11,000	
- Modules and centrifugal pump		10,000
- 50m pipe	50	50
Depth to water table (m)	8	3
Horsepower used (hp)	0.75	0.75
Economic life (years)	15	15
Time operated/year (hrs)	1,500	1,500
Pump capacity (m^3/hr)	9.6	32
Annual pumping (m^3)	14,400	48,000
Interest on capital (%)	10	10

Table 4. Cost Calculations for Pumping

Item	Solar	
	-8m Level	-3m Level
	..................US$/year..................	
A. Fixed Cost		
Depreciation:		
-8m US$12,350/15 years	823	
-3m US$10,050/15 years		670
Interest:		
-8m US$12,350*0.10/2	618	
-3m US$10,050*0.10/2		503
Sub-total	**1,441**	**1,173**
B. Variable Cost		
Repair and Maintenance	120	80
Sub-total	**120**	**80**
Total Cost/year	**1,561**	**1,253**
Cost/m^3 Pumped (US$)	**0.10**	**0.03**

9. From the cost analysis in Table 4 it is apparent that solar pumping for irrigation would become financial attractive in northern Sudan only at lifts below 3m. Such conditions exist extensively in the vicinity of the two Nile rivers where however either electric energy, or - due to internal development and thus infrastructure - diesel fuel is available. Both the latter energy carriers are considerably cheaper than solar energy driven systems.

Conclusion

10. Solar energy for pumping water in northern Sudan is financially uncompetitive to diesel or hand powered pumps, even though it is financially attractive on its own when considering very low lifts (< 3m).