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**An Energy and Economic Analysis
of Irrigation Systems**

G. Stanhill, H.J. Vaux, Jr.

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Table of Contents

Page Number

a.	Cover page	1
b.	Table of contents	2
c.	Abstract	3
d.	Objectives of the research	6
e.1	A comparison of the energy requirements of different systems of irrigation	
e.2	Gross energy requirements for recycling municipal sewage water through the aquifer - a case study of the Israel coastal plain project.	30
e.3	An economic and energy analysis of irrigation in California and Israel.	50
f.	Description of cooperation	106
g.	Main achievements of the research	107
h.	List of publications	109

AN ENERGY AND ECONOMIC ANALYSIS OF IRRIGATION SYSTEMS

Abstract The energetic consequences of substituting modern low-pressure installations for the older high-pressure sprinkler irrigation systems were examined for two major crops as grown in different regions of Israel. The indirect energy use, represented by amortization of the irrigation system, increased by between 2.0 and 2.5 GJ ha⁻¹Y⁻¹ when a spray system was substituted for a sprinkler system in a citrus orchard, and by about 7.0 GJ ha⁻¹Y⁻¹ when drip lines in a cotton crop were substituted for an overhead sprinkler system.

A reduction of the hydraulic pressure at the farm gate of the supplied irrigation water to the level required for a spray installation (350 kPa) would save 8% on the total energy for irrigating a citrus orchard. This amounts to a saving of 5 to 7 GJ ha⁻¹Y⁻¹ in the central region of the country and a saving of 11 to 34 GJ ha⁻¹Y⁻¹ in the southern regions.

A further reduction of the hydraulic pressure of the supplied irrigation water to the level required for drip lines (200 kPa) will save 16% on the total energy used for irrigating a cotton crop. This would amount to a saving of 4 to 8 GH ha⁻¹Y⁻¹ in the northern regions and a saving of 12 to 38 GH ha⁻¹Y⁻¹ in the southern regions of Israel.

The energy cost of recycling municipal sewage water for irrigation through the aquifer was analyzed using data from Israel's central coastal plain project. The gross energy requirement for full tertiary treatment up till the inlet of the irrigation water distribution system was estimated to be 16 MJ m⁻³; 57% for pumping, 35% in the chemicals used for treatment and 8% for infrastructure amortization. Over half of this total could be attributed to the energy requirements for eliminating coastal pollution caused by sewage discharge.

The economic consequences of increases in the price of energy and constraints in energy supply on the profitability of irrigated agriculture was studied using a mathematical programming model and data from eight contrasting districts of California and Israel.

In a scenario in which the price of direct energy doubles, the NW Negev district in southern Israel would suffer more than a one-third reduction in net revenues. This is explained by the fact that this district is extremely energy intensive, has a crop mix which produces relatively lower net revenues than the other Israeli districts, and it currently enjoys a substantial subsidy in that the price of water is considerably lower than the cost of energy needed to convey it. Thus, unless further subsidies were provided as a means of effectuating Israel national policies of promoting settlement in rural areas, the district would suffer substantial adverse effects as a result of an increase in energy prices. The fact that NW Negev would suffer only modest reductions in net revenue with a constraint that reduced available energy by 20% and the low shadow price of energy under the constraint emphasizes the importance of the relatively low valued crop mix in that district.

The three remaining Israeli districts are about equally affected by both the assumed increase in energy prices and the imposition of a 20% reduction in available energy. This is attributable to the fact that all are relatively more profitable than the NW Negev and the California Districts. The two California districts, on the other hand, follow the Negev pattern in which net revenues are reduced more with an energy price increase than with the constraint. Although this pattern is not as dramatic in California as with NW Negev, the explanation lies with relatively less profitable cropping patterns in these districts.

Analysis showed that the climatically induced differences in evapotranspiration and cropping patterns and the current levels of energy prices were the major factors determining the size of these responses.

Objectives of the research

Four objectives were set out in the original research proposal. The first three were the determination of the gross energy requirements of, respectively, the different sources of irrigation water transport and storage systems and irrigation application methods used both in Israel and the irrigated western states of America. The fourth, integrating objective was to use this information in a model to be developed and tested for the prediction of the total energy requirements for different methods of irrigation. The use of the model and data base should enable the energy cost of water saved by the adoption of advanced irrigation technology to be assessed.

These objectives were considerably modified as a result of the comments and suggestions of the reviewers' reports and because of the significant cuts made in the level of funding to one third of that requested and in the duration of three years.

In the modified program process energy analysis studies were confined to Israel and restricted to the examination of alternatives available for immediate implementation. These included a study of the energy requirements for the manufacture of drip, spray and sprinkler irrigation equipment and the energetic implications of changing from one system of irrigation to another as applied to the two major irrigated crops in Israel in their major locations. The second objective was to analyze the energy cost of irrigation with municipal sewage water recycled through the aquifer in the central coastal plain project.

The element of economic analysis was markedly strengthened by including as an objective the development of a model which would allow the effects of increasing energy costs and decreasing energy availability on the net returns from irrigated agriculture in California and Israel to be examined. This major objective of the project was realized with data from eight irrigation districts in both states displaying widely varying intensities of water and energy use.

A COMPARISON BETWEEN THE GROSS ENERGY REQUIREMENTS OF VARIOUS IRRIGATION SYSTEMS

E. Stibbe

Abstract

The energy requirements for manufacturing irrigation equipment in Israel was evaluated from a survey of a number of local factories and workshops.

Based on the results obtained and the evaluated life expectancy of components the annual amortization of energy by high-pressure (sprinklers), medium-pressure (undertree sprinklers and sprayers) and low-pressure (drip lines) irrigation systems as used locally for irrigating citrus orchards and cotton was calculated. For citrus orchards a low-pressure sprayer system amortized $1.5 \text{ GJ ha}^{-1} \text{ y}^{-1}$ more energy than a medium-pressure undertree sprinkler system, and $2.7 \text{ GJ ha}^{-1} \text{ y}^{-1}$ more than a high-pressure, overhead sprinkler system. For irrigating a cotton crop a low-pressure dripline system used $6.8 \text{ GJ ha}^{-1} \text{ y}^{-1}$ more indirect energy than a movable, high-pressure overhead sprinkler system.

The yearly energy invested in irrigation water conveyance (National Water Carrier), with the current hydraulic pressure of 500 kPa at the farm gate varies for a cotton crop from 25 to $50 \text{ GJ ha}^{-1} \text{ y}^{-1}$ in the northern regions and from 75 to $235 \text{ GJ ha}^{-1} \text{ y}^{-1}$ in the southern regions of Israel. For a citrus orchard this energy input varies from 65 to $80 \text{ GJ ha}^{-1} \text{ y}^{-1}$ in the central region and from 135 to $415 \text{ GJ ha}^{-1} \text{ y}^{-1}$ in the southern regions. Thus the annual energy amortization of a dripline irrigation system in the north amounts to 1/3 of that expended on water conveyance but in the southern regions amounts to only 1/18th, indicating the large regional dependency of energy inputs for irrigation.

Calculations show that the reduction in energy requirement for water conveyance needed by irrigation systems operating at lower

pressures more than compensates for their higher energy losses in amortization. The substitution of medium-pressure undertree sprinkler systems for high-pressure overhead sprinkler systems was for example calculated to save 8% on the total energy expenditure for water conveyance to the farm gate. This would amount to a saving of 5 to 7 GJ ha⁻¹y⁻¹ for citrus in the central region and 11 to 34 GJ ha⁻¹y⁻¹ for the southern regions. Dripline systems substituted for high-pressure overhead sprinkler systems in cotton could save 16% on the total energy expenditure for water conveyance. This would amount to a saving of 4 to 8 GJ ha⁻¹y⁻¹ in the northern regions increasing to 12 to 38 GJ ha⁻¹y⁻¹ in the southern regions.

Introduction

Recent standardized methods for the investigation of energy use have been proposed. Such calculations can lead to a more efficient use of the limited amount of energy and may prevent unnecessary wastage. Although such calculations are independent of monetary and economical values they may serve as additional information to complement economical evaluation (IFIAS, 1974).

In this report a comparison was made of the yearly amortization of energy embodied in different types of irrigation equipment used in a cotton field and a citrus orchard with the recommended amounts of water for each crop. In this investigation the energy requirements of the following four components were evaluated:

- a) the energy required for irrigation water supply to the two major irrigated crops in various parts of the country;
- b) the energy required for imported raw materials and fuels including their transport to Israel;
- c) the energy required to manufacture the components for irrigation systems from imported raw materials;
- d) the yearly amortization of energy per ha of a given irrigation system used for irrigating cotton or citrus orchards.

In many studies the amount of energy is expressed as weight of oil equivalent, but in this report the units for expressing quantities of energy adopted, were the physical one viz the joule. One mega joule (MJ) is equal to 2.52×10^{-2} kg of oil equivalent.

Results and Discussion

I. The evaluation of the energy requirements for irrigation water supply to two crops

For the sake of comparison, it was assumed that the fruit bearing citrus orchards were irrigated annually with a quantity of $7,200 \text{ m}^3 \text{ ha}^{-1}$ and the cotton crops with a quantity of $4,050 \text{ m}^3 \text{ ha}^{-1}$ during the growing season in all parts of the country; these volumes represent the national annual average water allocations for irrigating these crops. The calculation was based on a water supply to the farm gate with a hydraulic pressure of 500 kPa.

The energy requirements of supplied water for irrigation only includes the invested energy for conveying water from its source to the farm gate in a closed pressurized circuit and does not include the annual energy amortization of the closed circuit itself. For the evaluation of the annual energy amortization of the closed circuit, pertinent published local data are lacking. However, taking a value of 80 MJ per invested USA dollar in a water supply circuit enables the calculation of the annual energy amortization of the water distribution system to be calculated (Herendeen and Bullard, 1974). Locally the closed circuit from the Lake Kinneret (water source) to Rosh Ha'ayin (center of country), a major segment of the National Water Carrier, represented an investment of 150 million USA dollars for its building in 1959-1963. This carrier conveys about $1,000 \times 10^6 \text{ m}^3$ water per year. With an assumed amortization period of 25 years, this leads to an approximated annual energetic amortization of 0.5 MJ

per m^3 water. This value only represents about 5% of the energetic requirement for conveying water from its source to the center of the country and shows that the exclusion of the annual energy amortization of the closed circuit from the evaluation will not materially affect the comparison.

In Table 1, the energy requirements for the quantity of irrigation water applied to a citrus orchard and a cotton crop are shown, calculated according to the consumed electric energy data for water conveyance as given by Dvoskin (1981).

The values shown in Table 1 show a sharp increase in energetic requirements for applied irrigation water with increasing distance from the water source. It also directs attention to the importance of the energy term especially in the southern part of the country, as the annual water allotments for irrigation in the southern districts are actually larger than the national averages used for the two crops, as a consequence of a longer growing season, lower annual precipitation and a higher annual potential evapotranspiration demand.

Modern irrigation equipment distributes water under low hydraulic pressures and with small rates of discharge. The hydraulic pressure to at the farm gate could then be lowered from 500 kPa to 350 kPa or even to 200 kPa using sprays or drip line systems. Jaegerman et al. (1981) estimated for Israeli conditions that the national average gross energy requirement for the supply of water is 17 MJ per m^3 water with a hydraulic pressure of 500 kPa at farm gate, and an average total

X lift of 1,830 kPa. Reducing the hydraulic pressure for water supply to 200 kPa as required for drip line irrigation equipment, could reduce the national average energy requirement for water conveyance by 16%. However, the National Water Carrier also supplies water to the industrial and urban sector and the implications of reduction in hydraulic pressure to these sectors has to be investigated. Treated sewage water, which is to be conveyed by a separate circuit over long distances to agricultural areas, could well consider a reduction in hydraulic water pressure at its deliverance point.

II. The evaluation of energy requirements for raw materials, primary and secondary fuels

In Israel all primary energy, such as crude oil and coal, as well as almost all raw materials such as metals and plastics, is imported. Raw materials have already passed some industrial processing abroad and this has to be added to the energy used in processing these materials locally as well as the transport energy both from abroad and to local industry and the consumer. In many cases, the origin of the imported articles are known and the energetic requirements for processing may be available from the international literature. Unfortunately, the secondary energy requirements for energy used in the local industry, such as electricity, gas (LPG) and fuels which are produced locally, are less well established.

In Table 2, the energy requirements of the raw materials and energy sources are given, partly derived from literature and partly

from local sources. These data are later used in computing the energy requirements for the end products and components of irrigation systems.

Aluminum requires a large energy input for its refinement from bauxite by the electrochemical process as do plastics in their high thermic requirements to obtain polymers from basic materials. Aluminum, however, is extensively recycled and thus end products may have a lower energy requirement than when produced from fresh imported aluminum ingots, as indicated in Table 2. The same will be true for other recycled metals, such as bronze, brass and steel.

III. Evaluation of the energy requirements for the components in irrigation systems.

To evaluate the energy requirements of the components of irrigation systems, a number of local factories were surveyed. Included were producers of pipes, sprinklers, sprayers, drip equipment, valves, etc. The survey consisted of evaluating the electricity, diesel oil, fuels, raw materials and the man-hours used per unit weight of end product. Difficulties were encountered in the assessment of the production energy requirement when an item is assembled from components with different crude materials; or components were produced in various workshops and assembled in another location. Similarly, assessment was difficult when one workshop deals with several production lines. Also, a disparity in energy consumption exists between older and more recently equipped

workshops or when different production methods are applied. For instance, a difference of 23% in energy requirement was found between two factories for an irrigation dripper, and of 15% for plastic pipes of the same size and quality. For a number of end-products, such as accessories made from plastics, only a range can be given.

In Table 3, the energy requirements for the local manufacture of end-products are given. Together with the energy requirement of the imported raw materials this gives the final energy requirement of the end product, generally termed the gross energy requirement (GER).

Energy requirements in local production may differ from those abroad since the secondary energy sources used in the industry are from imported crude oil. Electricity is an important secondary energy source for the manufacture of many plastic components.

The total energy requirement of an aluminum pipe is much higher per unit weight than that of a plastic pipe. On the other hand, the amortization period of an aluminum pipe (15 years) is much longer than that of a plastic pipe (5-6 years) and the material for aluminum pipes can be recycled.

Sprinklers, sprayers and drip equipment have relative high energy requirements because of the metal and plastic materials incorporated in the end-product and the electricity used for the extrusion and injection moulding processes. Invested labor per kg item of water distributors is relatively high because of the manual assembly of components in sprinkler and sprayers, testing and packing.

IV. Evaluation of the annual energetic amortization of selected systems.

Many possible designs for irrigation installations have been proposed, with the older designs tending to be more labor-intensive, whereas newer designs are directed to reduce manual labor by automation. From the many designs described by Shani et al. (1980) a few designs commonly used to irrigate a citrus orchard and a cotton field have been selected.

The designs selected for citrus were an overhead sprinkler system; an under-tree, low angle sprinkler design and an under-tree sprayer design. For cotton, a movable overhead sprinkler design and a drip line irrigation design were selected.

Systems operating on low hydraulic pressure and small discharges, normally need a pressure control head and a filter system to prevent clogging of the water outlets.

Further automation is needed for fertilizer injection and semi-automatic closing of the water supply at the head of the field.

In assessing the annual energy consumption represented by amortization of an irrigation system, the length of life of the various components in the system is needed. At a particular location the quality of supplied water affects this by causing abrasion or chemical corrosion of sensitive parts and the amortization periods suggested by the manufacturers may be exaggerated.

For the systems evaluated, the life expectancy for metal pipes, meters, valves, accessories and sprinklers were taken to be from 10 to

15 years. For plastic pipes, accessories and water distributors amortization was assumed to be from 5 to 10 years, and for plastic sprayers and drip lines from 3 to 5 years. The field experience with respect to life expectancy of recently introduced plastic systems is limited.

The annual amortizations of energy invested in various irrigation systems used in citrus and cotton are given in Table 4, and the annual labor used for manufacturing and installation of the equipment in the field is presented in Table 5.

Results show that a permanent citrus overhead irrigation installation without fertilizer injection has a somewhat smaller amortization of invested energy than the more automated systems. On the other hand, the overhead sprinkler irrigation of a cotton crop with movable laterals has much lower amortization in comparison to a semi-automated drip installation with fertilizer injection.

There is however an important interaction between energy amortized in different irrigation systems and their energy requirements for water application. For example, undertree sprayer systems for citrus and drip lines for cotton have a higher annual amortization, but the water could be delivered to the crops at lower hydraulic pressure, requiring a pressure at the farm gate of 200 kPa.

This reduces that of the current distribution head by 300 kPa, equivalent to 16% ($= \frac{300 \text{ kPa}}{1830 \text{ kPa}} \times 100\%$) in the average total lift of the national water carrier.

Furthermore, semi-automated irrigation systems with provision for fertilizer injection save 1 man-day $\text{ha}^{-1}\text{y}^{-1}$ labor. This saving may be trivial in citrus orchards in comparison to the total amount of labor expended in cultivation and picking (the national average is about 70 to 90 man-days $\text{ha}^{-1}\text{y}^{-1}$) but is comparatively more important in cotton fields with their national average requirement of 10 to 12 man-days $\text{ha}^{-1}\text{y}^{-1}$ for crop management (CBS yearbook).

In the northern part of the country the annual amortization of energy invested in irrigation equipment forms a relative high percentage of the annual energy requirements for applied irrigation water but it is a comparatively minor item in southern districts, where the energy requirement for supplying irrigation water are high.

For a cotton drip irrigation in the north this percentage is 32% compared with 6% in the south. For a citrus orchard irrigation systems in the center of the country, the percentage is 14 against 3 in the south.

Low pressure irrigation systems such as under-tree sprayers for citrus and drip system for cotton require more labor in local manufacturing as well as for installing the systems in the field.

Data on the annual energetic amortization of different irrigation systems in California, U.S.A. (Table 6), has appeared in the literature and comparable systems show generally lower values than the calculated data presented in this report.

Reasons for the lower energetic amortization in California could include a lower energy requirement for electricity and raw materials

than those for Israel. Also, the different design of the equipment needed in an installation and a different evaluation of the life expectancy of various components may be a factor.

Conclusions

Energy requirements for irrigation water in Israel are high partly because water is conveyed in a pressurized circuit, and delivered at 500 kPa pressure at the farm gate throughout the country. Modern irrigation installations, operating at low hydraulic pressure and low discharge rates at the field outlet, require a lower hydraulic pressure than that currently supplied. Widespread adoption of low pressure irrigation could reduce the national average water lift for conveyance by 16%, saving an equivalent percentage of energy.

The gross energy requirements for a number of essential components of irrigation system have been determined by surveying local factories and workshops. The survey estimated the raw materials and energy sources used for manufacturing and the labor required to produce the end-product.

These data formed the basis for calculating the annual energetic amortization of a number of commonly used irrigation systems. The results show that automation and designs for low hydraulic pressure operation increases the annual energetic amortization. For example, the indirect energy use, represented by amortization of the irrigation system, increased by between 1.5 and 2.7 GJ ha⁻¹y⁻¹ when a spray system was substituted for a sprinkler system in a citrus orchard, and

by about $6.8 \text{ GJ ha}^{-1}\text{y}^{-1}$ when drip lines in a cotton crop were substituted for a movable overhead sprinkler system.

A reduction at the farm gate of the hydraulic pressure of the supplied irrigation water to the level required for an undertree sprinkler system (350 kPa) could save 8% on the total energy requirement for water supply to the farm gate (350 kPa for hydraulic pressure plus 1330 kPa for national average pumping depth instead of 500 kPa plus 1330 kPa at present). For irrigating citrus orchards in the central region of the country this amounts to a saving of 5 to 7 $\text{GH ha}^{-1}\text{y}^{-1}$ and a saving of 11 to 34 $\text{GJ ha}^{-1}\text{y}^{-1}$ for those in the southern regions.

A further reduction of the hydraulic pressure of the irrigation water required for drip lines (200 kPa) could save 16% on the total energy for water supply to the farm gate. This would amount to an average saving of 4 to 8 $\text{GJ ha}^{-1}\text{y}^{-1}$ for irrigating a cotton crop in the northern regions for irrigating a cotton crop and of 12 to 38 $\text{GJ ha}^{-1}\text{y}^{-1}$ in the southern regions of Israel.

In southern regions a larger indirect energy investment in modern, low pressure irrigation equipment would, therefore, be compensated by a substantial saving in energy expended on water conveyance.

The calculated annual energetic amortization values for the irrigation equipment in Israel were found to be higher than for those reported for California in the literature. This could be explained by the transport energy used in importing raw materials and primary

energy sources and the lower values for life expectancy of components adopted locally due to the more corrosive water.

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Table 1: The annual energy requirements for applied irrigation water to citrus orchards and cotton fields in various districts^{*}

Districts	Energy requirements of applied water ($\text{GJ ha}^{-1} \text{y}^{-1}$)	
	Cotton crop ($4050 \text{ m}^3 \text{ ha}^{-1} \text{y}^{-1}$)	Citrus orchard ($7200 \text{ m}^3 \text{ ha}^{-1} \text{y}^{-1}$)
Hula	24	-
Gilboa	49	-
Hadera	46	82
Ra'anana	-	63
Rehovot	-	82
Lachish	75	133
NaNegev	234	416

^{*} Irrigation water supplied to farm gate at a hydraulic pressure of 500 kPa. Energetic requirement for electricity is taken as $14.7 \text{ MJ kWh}_e^{-1}$ (Jaegerman et al., 1981).

Table 2: Energy requirements for imported raw materials and energy sources

Item	Source	Energy requirement	
Crude oil	(1)	50	MJ kg ⁻¹
Bronze	(1-3)	60-70	"
Brass	(1-3)	160	"
Aluminium	(1-3)	280	"
Plastics	(2)	110-190	"
Gas LPG	(3)	58	"
Diesel oil	(3)	53	"
Electricity	(4)	14-15	MJ kWh ⁻¹

Sources: (1) Leach (1975); (2) Kindler & Nikles (1979); (3) Dawson (1978); (4) Jaegerman et al. (1981).

Table 3: Energy requirements (MJ kg^{-1}) for local production of irrigation system components and labor (man-min kg^{-1}).

Items produced and processes used (numbered)		For imported materials	For local manufacturing	Total for end product	Labor for local manufacture
1. Coated steel pipes	1)	49.8	2.3	52.1	4.3
2. Aluminum pipes	1)	280.0	33.7	313.7	-
3. Zn-Al alloy couplings	2)	68.0	16.8	84.8	5.5
4. Plastic accessories and parts from:	3)				
a) polypropylene		115.0	10-20	125-135	0.1-0.5
b) P.V.C.		69.0	"	79-89	"
c) polyamid 6		194.7	"	205-215	"
d) " 6.6		183.7	"	194-204	"
e) polyformaldehyde		133.8	"	144-154	"
5. Valves:	2)				
a) bronze 2"-3" manual operated		70.8	16.2	87.0	5.5
b) iron 4" manual operated		40.4	18.1	58.5	6.0
c) bronze 2" hydr. autom.		58.1	16.8	74.9	4.2
d) iron 3" hydr. autom.		33.4	16.8	50.2	3.8
6. Plastic pipes:	4)				
a) 40 mm PE-HD		118.2	11.6	129.8	3.0
b) 32 mm PE-LD		111.4	11.2	122.6	2.0
c) 16 to 20 mm PE-LD		111.4	9.4	120.8	1.2
d) 16 to 20 mm PE-LD + emitters at 1 m distance		111.5-119.0	12.0-15.0	123.5-134.1	1.3
7. Sprinklers, sprayers	5)				
a) overhead, general purpose sprinklers 2.15 sprinklers/kg		65.0	47.3	112.3	19.8
b) undertree, low angle sprinklers 5.88 sprinklers/kg	6)	67.0	70.5	137.5	36.0
c) undertree, turbo.	3)				

המשרד הכלכלי
למעשה הכלכלית
1957

hammer sprinkler + spike	69.8	73.2	143.0	40.7
10.0 sprinklers/kg				
d) undertree sprayer 3)				
+ spikes	100.7	80.9	181.6	47.4
20.5 sprayers/kg				
e) undertree sprayer 3)				
+ spikes	107.5	26.8	134.3	52.7
21.7 sprayers per kg				

1) roll-welding; 2) casting; 3) injection moulding; 4) extrusion;
5) casting and lathe work; 6) casting, lathe work, injection moulding.

Table 4: The annual amortization of energy invested in irrigation systems irrigating citrus and cotton.

Type of irrigation system	Annual amount of energy invested in system (GJ ha ⁻¹ y ⁻¹)			
	Submain, riser gate valve	Control head	Laterals, risers, sprinklers accessories	Total
I <u>Citrus orchard:</u>				
a) Overhead sprinklers spacing 18x12 m plastic laterals galv. iron risers (perm.)	4.43	0.12	5.01	9.56
b) Undertree sprinklers spacing 8x6 m fertilizer injection plastic laterals & risers	3.21	0.30	7.21	10.72
c) Undertree sprayers spacing 4x6 m fertilizer injection plastic laterals & spikes	3.21	0.30	8.70	12.21
II <u>Cotton:</u>				
a) Overhead sprinklers spacing 12x18 m aluminum laterals (moving) risers	3.03	0.04	3.54	6.61
b) Drip lines, plastic spacing 1x2 m fertilizer injection	2.91	0.25	10.21	13.37

Table 5: Local labor requirements for manufacturing and field installation of irrigation systems.

Type of irrigation system	Local labor requirements (man days ha ⁻¹ y ⁻¹)		
	For manufact.	For field installation	Total
I <u>Citrus orchard:</u>			
a) Overhead sprinklers spacing 18x12 m plastic laterals galv. iron risers (perm.)	2.8	0.6	3.4
b) Undertree sprinklers spacing 8x6 m fertilizer injection plastic laterals & risers	2.6	0.9	3.5
c) Undertree sprayers spacing 4x6 m fertilizer injection plastic laterals & spikes	4.1	1.2	5.3
II <u>Cotton:</u>			
a) Overhead sprinklers spacing 12x18 m aluminum laterals (moving) risers	2.1	0.6	2.7
b) Drip lines, plastic spacing 1x2 m fertilizer injection	2.2	0.7	2.9

Table 6: Annual energetic amortization of comparable irrigation system in California.

Irrigation system	GJ ha ⁻¹ y ⁻¹	
	I [*]	II ^{**}
Solid set sprinklers	6.0	-
Hand moved sprinklers	0.8	3.0
Trickle lines	4.2	-
Lateral move with low pressure sprayer	-	8.4

* Batty and Keller (1981) Selected and converted data.

** Hagan and Roberts (1981) Selected and converted data, using the value of 12 MJ kWh⁻¹ for electricity as evaluated by Roberts and Hagan (1975).

GROSS ENERGY REQUIREMENTS FOR RECYCLING MUNICIPAL SEWAGE WATER
THROUGH THE AQUIFER FOR IRRIGATION - A CASE STUDY OF THE
ISRAEL CENTRAL COASTAL PLAIN PROJECT

E. Stibbe

Abstract

The energy required for tertiary treatment to recycle municipal sewage water from the Dan region so that it can be reused in either agriculture or industry has been assessed.

This assessment includes the annual amortization of embodied energy in the sewage conveyance circuit from city to plant, in the water treatment facilities of the plant, and in the groundwater recharge and recovery facilities, as well as the electrical energy to operate the system and the embodied energy in the chemicals to treat sewage water.

In 1981/82, the year under study, the gross energy requirement (GER) for full tertiary treatment to the gate of the distribution circuit and including groundwater recharge and recovery was 16.0 MJ/m^3 . Electrical energy subsumed 57% of the total GER, 35% for chemicals used in the treatment and 8% for energy amortization in the infrastructure.

Secondary treatment and disposal to the sea would require 9.2 MJ/m^3 , whereas primary treatment and sea disposal at the same plant had a gross energy requirement of only 3.9 MJ/m^3 .

The operational energy input of 14.7 MJ/m^3 required to recycle sewage water, so that it is suitable for restricted use as an addition to the total water budget of Israel, is high, compared with the operational energy input of 10.2 MJ/m^3 for the presently used water supply in the same region as the sewage plant. However, in addition to enlarging the water budget, the recycling process of sewage water eliminates the environmental pollution of the coast. A minimum energy requirement of 3.9 MJ per m^3 for the elimination of coastal pollution is calculated.

The labor requirement for recycling sewage water at present - $0.60 \text{ man-days/1000 m}^3$ - is large compared with the $0.19 \text{ man-days/1000 m}^3$ needed for potable water in the same district, and constitutes an important element in the cost of upgrading municipal sewage water for agricultural and industrial reuse.

Introduction

The central coastal district of Israel, with a population of 1.64 million, produced a sewage volume of $102.7 \times 10^6 \text{ m}^3$ in 1982 (Anon., 1983). Within this district a conglomerate of ten associated municipalities (the greater Tel Aviv area), with a population of 1.02 million producing a sewage volume of $72.7 \times 10^6 \text{ m}^3$ a year, has established a sewage treatment plant to start recycling sewage water, which is currently disposed of into the sea (see Table 1).

/ Table 1 /

The first stage of this project, which plans to treat eventually all sewage water produced has been in operation since 1977. In 1982, it had a raw sewage intake of about $60,000 \text{ m}^3$ per day.

One of the important motives for this project is to stop further pollution of the sea and beaches in this region as well as to augment the limited volume of water available for irrigating agricultural crops in the south.

The recycling process for sewage water consists of an initial aeration stage with subsequent settling in lagoons, followed by a flocculation and sedimentation treatment with lime and magnesium chloride, a further settling period in lagoons, followed by more aeration for ammonia gas release and atmospheric recarbonation resulting in a lowering of the pH. Finally, water is conveyed to infiltration basins for ground water recharge to a shallow aquifer. After a retention time of some months it will be pumped by a number of peripheral pumping stations to a pressurized conduit pipe for conveyance southwards for ultimate use in irrigation or industry (see Fig. 1).

/ Fig. 1 /

The quality of the recycled water is such that it is suitable for general agriculture and industrial use, as shown by data presented by Idelovitch et al. (1983) and Grinwald (1980).

The sewage treatment procedure adopted for recycling municipal sewage mainly reduces its high organic matter and the N and P concentrations. The chemical oxygen demand (COD) decreases from about 680 to 50 mg/l, the biochemical oxygen demand (BOD) from about 300 to almost nil, and N-NH_4 from about 50 to 5 mg/l (Grinwald, 1980). The adopted treatment in this plant produces recycled water with a total dissolved salt content (TDS) of 550-600 mg/l, a SAR between 7 and 8, an electrical conductivity (EC) of ~ 0.95 dS/m, a chlorine content of 200 mg/l, and a sodium content of 125 mg/l. This composition is similar to the average tap water quality supplied to the consumer. Fluctuations in water quality during the year occur and depend on retention time in the aquifer, the well's distance from the infiltration basins, the depth of the aquifer, and the degree of admixture with natural water (Idelovitch et al., 1983). Treated sewage water prior to infiltration into the soil would be sufficiently upgraded for irrigating certain crops (fodder, fiber and seed crops) by surface methods, and would require only 55% of the gross energy requirement necessary for tertiary treated sewage water (see Table 5). However, for food crops, or if sprinkler- or drip-irrigation is used, tertiary treatment is necessary (Hagan and Roberts, 1980).

The recycling of sewage water requires an input of energy for the conveyance of sewage from the municipalities to the plant, for the upgrading process in the plant, and finally for the groundwater recharge and the pumping of aquifer water. Additional energy inputs include those

needed to transport materials other than water (e.g. chemicals), as well as for the lighting and air-conditioning of buildings.

In addition to the energy invested in processing the water, accounting of the embodied energy invested in pipelines, plant installations, pumping stations, etc., and degraded in annual amortization, is required. In this paper the results of an analysis of the fossil energy requirements of the Dan Region Project for conveying and treating municipal sewage is presented, based on the sixth year of operation. The calculations are presented in energy units per unit volume of treated sewage water. It should be stressed that the original gross energy requirement embodied in the water received by the municipalities (10.2 MJ/m^3) has not been included in any of the following calculations. Such an analysis may provide both a clear picture of the partitioning of the energy sources and sinks, and a method of assessing possible options which are not available from a conventional economic analysis.

Methods

Basic data were obtained from both foreign literature sources and some local sources when available, and from energy analyses of local production processes (see Table 2).

/ Table 2 /

Data on electricity consumption, raw sewage intake, sea disposal, losses and recharged treated sewage, added chemicals, etc., for the treatment plant, were obtained from the annual report of the Mekorot Water Company (Kenrak and Marcovitch, 1982).

Electricity consumption for pumping from city to site were obtained from the sewage departments of the municipalities concerned.

The processes adopted for upgrading raw sewage, pollutant concentration control, and the layout of the plant, are described by Idelovitch et al. (1983). Essentially, the upgrading of sewage is obtained by aeration, flocculation and sedimentation, followed by aeration and recarbonation of the effluent. A final filtration through a sand dune profile lowers the pollutant concentration to values acceptable for limited reuse of recycled water. The 220-ha lagoon area is laid out on nonproductive land of low value and sufficiently far removed from urban centers not to cause public nuisance. The total annual energy requirement of a unit volume of treated sewage was obtained by adding an estimate of the annual amortization energy requirement (AAER) of the entire system to that of the annual operational energy requirements (AOER) of the processes involved.

Annual Amortization Energy Requirements (AAER)

Raw sewage from the municipalities is conveyed partly under pressure and partly by gravity flow in a closed circuit to the sewage treatment plant site. An estimate was made for the AAER of the various components of this conveyance system consisting of pipelines and pumping stations. Table 3 shows the estimated AAER value of the pipe system to be approximately 0.55 MJ/m^3 sewage.

/ Table 3 /

The AAER of the two pumping stations, one in Tel Aviv-Yafo and the other in Rishon le Ziyon, for conveyance of sewage to the treatment plant, was evaluated on the basis of the 1980/81 budget (Kenrak and Marcovitch, 1982). In this the depreciation value of the Tel Aviv-Yafo pumping plant was given as $\text{U.S.}\$11.33 \times 10^3$ for the conveyance of $3.26 \times 10^6 \text{ m}^3$ raw sewage, i.e., a cost of $\$0.0035/\text{m}^3$. Hagan and

Roberts (1981) estimated the annual energy depreciation cost of a pumping plant over a period of 16 years as 24.48 MJ/\$ given as 2.04 Kwh of electricity per \$). Using this value, the AAER of the pumping stations was then evaluated at 0.086 MJ/m^3 of raw sewage pumped through by the two stations.

Part of the treatment plant installation is the 220 ha lagoon area. If an estimate of $7.5 \times 10^3 \text{ MJ/ha}$ for soil preparation (Torgerson et al., 1983) is assumed, then this lagoon area, which is used for between 19 and $23 \times 10^6 \text{ m}^3$ sewage water per year and has a life expectancy of 20 years, has an AAER of about 0.004 MJ/m^3 .

The mechanical installation of the treatment plant consists of five pumps, a lime reactor and an effluent aerator for ammonia removal and recarbonation. On the basis of the 1980/81 budget (Kenrak and Marcovitch, 1982), the AAER value was \$0.49 million for a treated volume of $23 \times 10^6 \text{ m}^3$ raw sewage, or $\$0.021/\text{m}^3$. Using again the depreciation value for a pumping plant given by Hagan and Roberts (1981), an AAER of 0.16 MJ/m^3 treated sewage is obtained.

The 16 peripheral wells for treated sewage water recovery from the aquifer around the infiltration area, pumped about $12 \times 10^6 \text{ m}^3$ water in 1982, consisting only partially of treated sewage water. Eventually all water pumped will originate from recharged treated sewage water. Assuming an average well capacity of $250 \text{ m}^3/\text{h}$, depth of 30 m, pumping lift of 75 m, cost of the electric motor and pump = \$25,000, cost of well development = \$25,000, and a depreciation time of 16 years, the total invested costs will be \$0.8 million for 16 wells. Again, using the value of 24.48 MJ/\$ for annual energy depreciation cost of pumping plants (Hagan and Roberts, 1981), an AAER of $5.87 \times 10^6 \text{ MJ}$ is obtained, equivalent to 0.49 MJ/m^3 when expressed per unit pumped volume.

The total AAER value calculated was 1.33 MJ/m^3 for all embodied energy in the city-site conveyance system, plant installations and reclamation pump systems (see Table 4).

/ Table 4 /

Annual Operational Energy Requirements (AOER)

The main energy expenditure for operating the entire system of sewage conveyance, sewage treatment and recovery from the aquifer is attributable to the use of electricity and chemicals. Electrical energy use by a pump station for raw sewage conveyance of $22.9 \times 10^6 \text{ m}^3$ from the Tel Aviv-Yafo municipality to Holon-Bat Yam was $1.02 \times 10^6 \text{ KWh}_e$, i.e., $0.05 \text{ KWh}_e/\text{m}^3$ or 0.73 MJ/m^3 . (For sources, see Acknowledgements.)

For an annual intake by the treatment plant of $22.9 \times 10^6 \text{ m}^3$ of raw sewage, $2.31 \times 10^6 \text{ KWh}_e$ electrical energy, i.e., $0.10 \text{ KWh}_e/\text{m}^3$ or 1.45 MJ/m^3 , was required for aeration and recirculation in lagoons (Kenrak and Marcovitch, 1982). During 1982 a small part of the sewage was disposed of to the sea after the first treatment and it was estimated that the energy required for pumping to the sea outlet was 0.6 MJ/m^3 .

The largest volume of incoming sewage water undergoes a secondary and tertiary treatment for further removal of organic pollutants, phosphorus and nitrogen compounds. Electricity expenditure for the flocculation and sedimentation processes, followed by aeration for ammonia removal and recarbonation, required $0.3 \times 10^6 \text{ KWh}_e$ for a volume of $18.5 \times 10^6 \text{ m}^3$, i.e., $0.016 \text{ KWh}_e/\text{m}^3$ or 0.24 MJ/m^3 (Kenrak and Marcovitch, 1982).

An additional energy requirement to be taken into account is for the embodied energy for the production and transport of lime and magnesium chloride. Lime is applied at the rate of 0.587 kg/m^3 to

sewage water (Idelovitch et al., 1983); it has an energy requirement of 8.83 MJ/kg (Jaegerman et al., 1981) for local production and 1.03 MJ/ton/km for local transport (Table 2) over a distance of 100 km, giving an estimate of 5.28 MJ/m^3 treated sewage water. Magnesium chloride had been applied at a rate of 0.05 kg/m^3 (on dry basis), with an inferred energy requirement of 5 MJ/kg (Table 2), giving about 0.25 MJ/m^3 . The two chemicals added for sewage treatment thus account for 5.53 MJ/m^3 .

After secondary treatment, the conveyance to the infiltration basins of $16.2 \times 10^6 \text{ m}^3$ sewage water with an additional $2.3 \times 10^6 \text{ m}^3$ pumped aquifer water, sequestered $2.463 \times 10^6 \text{ KWh}_e$, i.e., $0.133 \text{ KWh}_e/\text{m}^3$ or 1.93 MJ/m^3 (Kenrak and Marcovitch, 1982).

Pumping out the recharged aquifer water for limited reuse adds an additional energy requirement. Assuming an average electrical energy requirement per pump station (16 wells) of $0.0044 \text{ KWh}_e/\text{m}^3$ per meter lift (Batty et al., 1975), a ground water depth of 25 m and a desired hydraulic pressure of the recovered water of 50 m at the gate of the distribution conduit system, results in a lift requirement of 75 m and an energy need of $0.33 \text{ KWh}_e/\text{m}^3$ or 4.79 MJ/m^3 for the recovery of recharged treated sewage.

Annual gross energy requirements for sewage treatments

Summation of the amortization energy requirement and the operational energy requirement provides an estimate of the annual gross energy requirement of sewage water treatment. Although the plant is planned to treat all municipal water for restricted reuse, the process was subdivided into three treatment stages to show the increasing energy requirement for the successive options in the disposal of sewage water. The various stages are shown in Table 5.

The annual operational energy requirement for the tertiary treatment of sewage water is 14.67 MJ/m^3 . Taking into consideration that the operational energy requirement for electricity to supply potable water in the same region as the sewage treatment plant is $0.70 \text{ KWh}_e/\text{m}^3$, equivalent to 10.15 MJ/m^3 (Dvoskin et al., 1981), it becomes apparent that fully

/ Table 5 /

treated sewage for limited reuse requires 30% more fossil energy than potable water.

During 1982 the gross energy requirement for recycling water (i.e., both operational and embodied) was found to be 16.0 MJ/m^3 . For recharged secondary treated waste water and its reuse by pumping out the aquifer at a 50 m hydraulic pressure for sprinkler irrigation, there is an annual gross energy requirement of 12.41 MJ/m^3 (Hagan and Roberts, 1980). The energy requirement for electricity in California was estimated at 11.95 MJ/KWh_e (Roberts and Hagan, 1975), whereas the local estimate of $0.273 \text{ kg oil/KWh}_e$ (oil having an embodied energy of 51.8 MJ/kg) gives 14.2 MJ/KWh_e (Jaegerman et al., 1981).

Labour requirements for recycled sewage

The labour force employed in conveying the sewage from the municipalities to the plant, at the plant, totalled 37 workers (for sources, see Acknowledgements). If all recharged treated sewage water could be reclaimed, and assuming 300 workdays per year, then the labour requirement for recycled water will be:

$$\frac{37 \times 300}{18.5 \times 10^6} = 0.60 \text{ man-days/1000 m}^3$$

This value is three times larger than that for the potable water supplied by the Mekorot Water Co. and local water authorities:

$\sim 0.19 \text{ man-days/1000 m}^3$. The labour requirement per unit water will, however, almost certainly decrease in the near future when the plant is in full operation.

Conclusions and Summary

Our exploitation of limited resources means that every additional water source in Israel is welcome, even if it falls in the category of "restricted water use" for agricultural and industrial purposes. It may be noted that in 1979 about 73% of the total water supply was directed to the agricultural sector, 22% to the domestic sector and 5% to the industrial sector (Anon., 1981).

The annual operational energy requirement for recycling municipal sewage water was estimated at 14.7 MJ/m^3 . The operational energy requirement for potable water in the Dan Region was estimated at $0.7 \text{ kWh}_e/\text{m}^3$, equivalent to 10.2 MJ/m^3 (Dvoskin et al., 1981). Although water is conserved by recycling sewage water, this process does not conserve fossil energy. However, taking into account the dual purpose of the recycling plant, it should be emphasized that the elimination of pollution of the coast sequesters an important fraction of the total energy input. This was estimated to be equal to the difference between the operational energy requirement for recycled sewage water (14.7 MJ/m^3) and that for potable water (10.2 MJ/m^3) minus the energy required to pump sewage to the sea outlet (0.6 MJ/m^3) if recycling had not been done. In other words, the energy cost for the elimination of coastal pollution is 3.9 MJ/m^3 recycled water for restricted use.

The annual gross energy requirement for recycling sewage water according to the process adopted by the Dan Region project was estimated at 16.0 MJ/m^3 . Electricity consumption for treatment of sewage accounted for 57%, chemical supply for 35%, and infrastructure for 8% of the total fossil energy requirement. Once the pipeline to the south is completed, additional energy has to be added to this gross energy requirement estimate to account for the conveyance of water

over a distance of approximately 100 km and for the embodied energy in the pipeline itself. Based on comparable distances and expected height differences, the additional energy cost is estimated to be approximately 25 MJ/m^3 .

In 1980/81 the cost of the reclaimed sewage water was evaluated to be about U.S.\$0.16/m³ (Kenrak and Marcovitch, 1982), which is about double the price paid by the farmers for fresh water delivered to the agricultural sector in this coastal district (Anon., 1981). Part of the high cost of reclaimed sewage water is due to the current high labour requirement of the recycling process.

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Fig. 1. Schematic sewage production and disposal balance to the sea and plant, of the ten associated municipalities for 1981/82.

(in 10^6 m^3 per year)

Table 1: Sewage production and disposal of the ten associated municipalities for 1981/82 (in 10^6 m^3 per year)

Municipalities	Sewage production	Treatment plant	Sea outfall
Petah Tiqwa			
Bene Beraq			
Ramat Gan	52.314	2.450	49.864
Givatayim			
Tel Aviv-Yafo			
Bat Yam			
Azur	15.100	15.100	-
Holon			
Rishon leZiyyon	5.300	5.300	-
Bet Dagan			
Total	72.714	22.850	49.864

Sources: Anon. (1983); Kenrak and Marcovitch (1982).

Table 2: Basic energy intensity data used in computations

Item	Energy intensity	Unit	Sources
Thermal energy for electricity	14.4	MJ/KWh _e	Leach and Slessor, 1976
Coated steel pressure pipes	35.0	MJ/kg	Dawson, 1978
Asbestos-cement pipes	15.0	MJ/kg	Batty and Keller, 1980
Electrical energy for pumping well water to a height of 100 m	0.44	KWh _e /m ³	Batty and Keller, 1980
Lime	8.83	MJ/kg	Jaegerman <u>et al.</u> , 1981
Magnesium chloride	5.0	MJ/kg	Inferred from KCI data of Leach and Slessor, 1976
Local road transport	1.03	MJ/ton.km	Jaegerman <u>et al.</u> , 1981.

Table 3: Annual amortization energy requirements for sewage conduits from municipalities to plant site (1982)

Pipe diameter- (inch)	Type of pipe *	GER (MJ/km pipe)	Total length (km)	Ann. amort. energy requir. (MJ/yr)	Annual conveyed volume (m ³ /yr)	Amort. energy per unit volume (MJ/m ³)
50	Steel, coated, pressure	12×10^6	10 (2 x 5)	8.0×10^6	5.3×10^6	
24	Steel, coated, pressure	4×10^6	3	0.8×10^6	2.5×10^6	
24	Asbestos-cement	7.5×10^6	10	3.8×10^6	15.1×10^6	
				$12. \times 10^6$	22.9×10^6	Avg. = 0.55

*Tel Aviv to Holon-Bat Yam, 50", 300 kg/m, life expectancy 15 years.

Rishon leZiyyon - plant, 24", 100 " " " "

Holon-Bat Yam - plant, 84", 500 " " " 20 "

Table 4: Annual amortization energy requirements for infrastructure.

Item	AAER (MJ/m ³)
Pump stations and piping for sewage conveyance from municipalities to site	0.676
Treatment plant installation and lagoons	0.164
Installation and development of reclamation wells	0.490
Total	1.330

Table 5: Gross annual energy requirements for three different levels of water purification of municipal sewage, based on reported data from 1982.

Stages	Annual energy requirements for different levels of water purification (MJ/m ³)		
	A **	B ***	C ****
I Annual operational energy requirements:			
a) From municipalities to treatment plant	0.73	0.73	0.73
b) Aeration-lagoons	1.45	1.45	1.45
c) To sea outfall	0.60	-	-
d) Coagulation-sedimentation and ammonia stripping-lagoons		5.77	5.77
e) To sea outfall		(0.60)*	-
f) Conveyance to recharge basins			1.93
g) Aquifer pumping to gate of distribution system			4.79
II Annual amortization energy requirements			
a) Conveyance equipment - city to site	0.68	0.68	0.68
b) Installation of treatment plant and recovery wells	(0.30)	(0.40)	0.65
III Annual gross energy requirement (Total of I + II)	3.76	9.03	16.00

* Figures in parentheses assume that these options are actually available.

** A Primary treatment with sea disposal.

*** B Primary and secondary treatment with sea disposal.

**** C Primary, secondary and tertiary treatment, recovery from aquifer, and reuse of water.

Description of cooperation

A high degree of both international and interdisciplinary cooperation was required to fulfil the objectives set out for this project. This cooperation was rendered more problematic by a number of initial difficulties. These included the need to change the cooperating investigator at a late stage in the preparation of the proposal because of the move to a new position by the original cooperator; the different professional background and interests of the new cooperator, and the significant cuts in the project budget and duration.

Active cooperation in a revised program was greatly facilitated by the visit of the US cooperator to Israel in March, 1983. Dr. Vaux visited extensively with Israeli economists and administrators responsible for agricultural water policy and became acquainted with the agricultural background in a series of field visits. He also participated in an international workshop on energy and agriculture held in Israel at that time. The visit by the Israeli investigator took place some nine months later, and during it the details of the joint comparative investigation of the energy sensitivity of the irrigated agricultures of California and Israel were finalized. The outstanding information required from Israel was identified and forwarded after the visit.

The completion of this analysis, and hence the preparation of the final report, were unfortunately delayed by a period of ill-health and the sabbatical leave of the US cooperator and apologies are offered for this delay.

Main achievements of the research

A major achievement of the research carried out was the development of a model to analyze the economic response of the irrigated agricultures of California and Israel to changes in the price and availability of energy. The model allowed quantification of the first order response of the net returns from a number of irrigation districts to change in the energy component. Application of the model to data from eight diverse regions of Israel and southern California demonstrated a wide range in their response.

In financial terms a doubling of the water related energy costs was calculated to lead to a reduction in annual net revenues ranging from between one to eighteen million US dollars (1981 prices), representing reductions of between 6 and 36%. A reduction of one fifth in the available direct energy was estimated to lead to a reduction in the annual net income ranging between two thirds of, and six million in the US dollars, representing percentage reductions between 3.5 and 10%. The reasons for these large differences between the districts were investigated and identified as being due to either climatically induced variations in evapotranspiration and cropping patterns and/or the widely varying costs of water and energy on the different districts.

Further refinements desirable in the model were identified: these included incorporation of the indirect energy requirements for irrigation and other direct and indirect energy inputs to crop production, as well as a consideration of the long term, feed-back responses to changes in energy price and availability.

The two energy analyses that were completed referred to two new options for water conservation in Israeli agriculture. The first concerned the substitution of drip and spray for sprinkler irrigation systems. The results of this study showed that for the two major irrigated crops studied, cotton

and citrus, and for the two regions examined, the increased energy invested in the low pressure irrigation systems could be more than compensated by the lower direct energy required for water distribution. This was especially so in regions where water conveyance is energy intensive. These results strengthen the view that energy conservation in Israel's irrigated agriculture requires a re-examination of the current policy of delivering all irrigation water at the high pressures needed for sprinkler systems.

The second energy analysis was of the gross energy requirements for irrigation water produced by the Central Coastal Plain Plan which treats municipal waste waters of the area by recycling through the aquifer to render them suitable for irrigation. The results of this study showed the gross energy requirement for the treatment, 16 MJ m^{-3} , was some 50% more than that invested in the water as supplied to the municipality. Almost two thirds of the energy requirement for treatment was electrical energy used for pumping. At the actual site of irrigation the total energy requirement of the water will be comparable to that of the most efficient desalination processes. Analysis showed that approximately 60% of the energy invested in recycling municipal wastewater should be allowed for as the treatment necessary to avoid coastal pollution by the discharge of untreated wastewater.

List of Publications

To date only the one paper listed below has been published. However, a second paper (see Section e.2) will shortly be submitted and it is hoped that the material presented in Section e.3 will form the basis of a third publication.

In addition, much of the information gathered within the course of this project has been used in the preparation of a book entitled "ENERGY AND IRRIGATION" to be published by the International Irrigation Information Center, Bet Dagan. Half of the projected chapters of this book have been written and it is hoped to complete the publication before the end of 1985.

- 1) E. Stibbe (1983) Comparing differences in the energy requirement of irrigation systems. (in Hebrew) Hassadeh, Vol. 64: 160-164.