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OPTIMAL OPERATION OF THE PUMPING STATIONS IN THE KINNERETH-ESHKOL SECTION OF THE NATIONAL WATER CARRIER

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INTRODUCTION

Description of the System

Water is pumped from the Kinnereth through the Eshed-Kinrot penstock into the Jordan Canal by means of three pumps arranged in series in the Eshed-Kinrot pumping station. Each pump is comprised of a vectorial centrifugal feed pump and a horizontal main pump. The main pumps are horizontal centrifugal single phase pumps with a double inlet. The pumps are situated 7.5 meters above maximum water level of thè Kinnereth and are fed by the feed pumps via two feed pipes, any may operate with the lake level as low as - 216 meters below sea level.
The water is pumped through a penstock (2,300 meters) and lifted through 250 meters into the Jordan Canal. The water gravitates along a slope of 0.00016 for 16 kilometers along a concrete lined canal of trapezoidal cross-section, and then flows into the Zalmon Reservoir. The reservoir is concrete lined and has a total volume of 880,000 m^3 with a minimum operational capacity of 217,000 m^3. (Equivalent elevations +39.34 m.a.s.l. to +35.95 m.a.s.l.).

The water is pumped out of Zalmon Reservoir by means of three vertical pumps operated by synchronous motors. The water passes through a 800 meters along penstock and reaches the Eshkol Canal at the elevation +149.34 meters. This canal is 18 kilometers in length, is concrete lined with a curved floor. The water flows along it into Eshkol Reservoir at the elevetation +145.40 m.a.s.l.

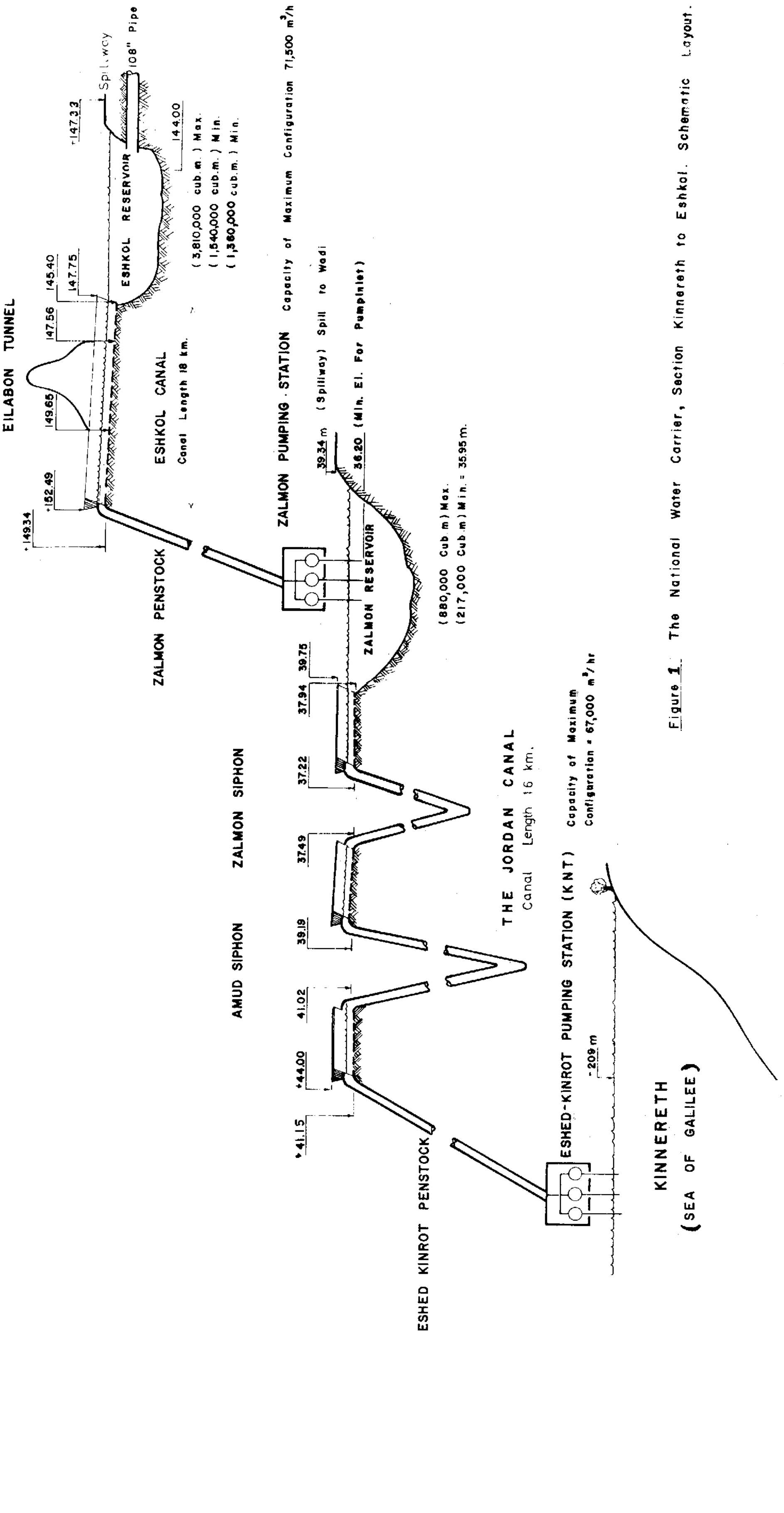


Figure 1. The National Water Carrier, Section Kinnereth to Eshkol. Schematic Layout.

Eshkol Reservoir has a maximum capacity of 3,810,000 m^3 and a minimum of 1,540,000 m^3 (elevations +147.0 m.a.s.l. and 144.000 m.a.s.l., respec.), with an operative volume of 1,270,000 m^3 disregarding the settling basin.

Certain hydraulic limitations on the activation of pumps are applied when the elevations in the canals reach specified values.

The present work considers Eshkol reservoir as the terminus of the system being examined. The water flows Southwards from Eshkol reservoir to Menashe station via a 108" pipe. This flow is governed by operational considerations of the Water Carrier and regional zones in the Central regions of the country. Quantities withdrawn from Eshkol are fixed outside this model.

A considerable part of these quantities is destined for recharging wells. This factor contributes to the constant hourly withdrawals over long periods.

Objectives

1. To devise a logical model which when given:
   - the existing physical system and all the constraints on its operation,
   - the known time-distribution of withdrawals from Eshkol reservoir,
   - the existing tariffs of electricity and the limitations imposed by the Electricity Company,
   - a specified objective function which considers the cost of electrical energy and, in addition, all other factors which make up the non-fixed part of the operating cost,

   will automatically decide on activations and deactivations of pump units and will then assist in determining the operating regime that will result in the best value of the objective function.
2. To determine the best operating regime for both normal and exceptional conditions.
3. To generate a large number of solutions for any conditions that may arise in the future.

Flexibility in Operation

Flexibility in the operation of the system is accorded by the relatively large storage available (both in the reservoirs and the canals) and due to the delay in response time caused by flows in canals.

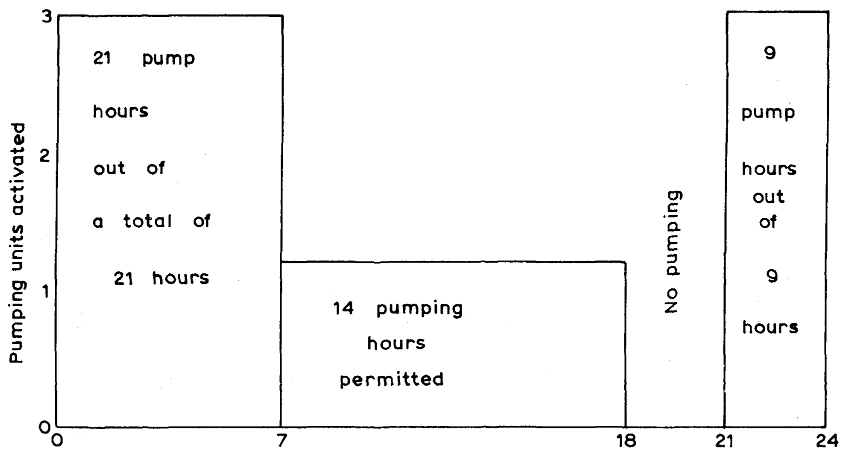
The operating regime at the reservoirs can be so adjusted that a specific elevation or range in elevations is preserved. High elevations contribute towards energy saving but constitute an element of danger if a power failure would allow the contents of the canal to empty into the reservoir without the facility of pumping therefrom, thus causing overflow. This element of danger requires, therefore, that a safety margin be observed, and also that the optimal value of the margin be determined.

Certain aspects of maintenance may further require the reduction of the level to a specified elevation for specified periods of time.

Other aspects of maintenance may require the dismantling of a unit, and the ability of the limited system to supply the required withdrawals must be examined.

The tariff regulations enforced by the Electricity Company constitute the greatest influence on operating requires. A maximum number of pump-hours/day are specified as are also the hours during which pumping is limited or disallowed.

A total of 44 pump-hours permitted out of a total of 72 hours.



Equipment Failure

From the statistical analysis of equipment failure data the following results were obtained.

Station	1/ hours	σ(logm.)	μ(logm.)	MIN. Hours	Prob.	Max. Hours	Prob.
K.N.T.	399	0.655	0.679	1	0.15	160	0.99
ZALMON	732	0.680	0.459	1	0.25	110	0.99
Total Power Failures	769	0.335	0.285	0.5	0.02	6.4	0.94

where

$1/\lambda$ = Mean time between failures

σ(logm.) = Standard Deviation of log. of repair times

μ(logm.) = Average of logs of repair times

MIN.,MAX. = Minimum and Maximum repair times.

The effect of a total power failure is to shut down all pumping operations at the K.N.T. and Zalmon pump stations. Furthermore the inability to balance the inevitable inflow of water from the canal to Zalmon reservoir by means of pumping at Zalmon Station may cause overflowing if the safety margin observed by the operating regime is (a) less than the volume of water in the canal, and (b) the power failure is of sufficient duration.

Policy of Operation

The motivating feature of the model is the set of "policies" adopted for the simulation. It is by taking these policies into consideration that the model is led into making decisions on the activations of pumping units, and subsequently into the computation of flows, levels and costs. We examine the feasibility and effectiveness of different sets of policies by the criterion of costs. We may therefore isolate the optimal policy whereby, say, we may be enabled to supply a 50% increase in the withdrawals from Eshkol.

The practices which constitute operating policies or from which operating policies may be built up of are:

1. Relaxation of Peak Hour Restraints. Under this policy a pump may be operated during an hour otherwise prohibited by the Electricity Company. Special permission has to be granted, and this is given when conditions on any given day allow.

2. Reduction of Minimum Level at Eshkol. The minimum level presented for purpose of defense and national safety is more stringent than that required by hydraulic restraints. At various times permission is given to change over from one minimum to the other. This change may be required to take place over a period of time with a different minimum specified for each day.

3. The Operative Tariffs
   The specific tariff applied by the Electricity Company and comprising the periods during which pumping is partially or wholly prohibited can be represented by means of a detailed list of availabilities for each pump at each hour of the week. In this way any tariff arrangement may be tested.

4. Set Points
   Various levels of water in the reservoirs may be stipulated at which different combinations of pumps are activated or deactivated. The effect of a particular group of settings on the ruling reservoir may be tested by the model, so that any predetermined ruling level may be obtained. Normally the settings are fixed at maximum so as to run the system on the highest levels possible.

The hazard of a complete power failure, however, warrants the introduction of some safety margin. We require therefore to determine that safety margin which will sufficiently reduce the danger of spillage without introducing unreasonable costs due to operating the pumps of Zalmon Station at a low level. This safety margin must also take into consideration the volume of water contained in the canal at any time. The problem thus reduces to determining the size of the "danger factor" that we are prepared to entertain.

The Model Characteristics

The computer program which implements the model has the following characteristics.

1. It simulates the performance of the hydraulic system linking K.N.T., Zalmon and Eshkol under varying operating policies and under conditions of unexpected failure in equipment and power supply.

2. It computes hourly volumes of water in canals and reservoirs, the hourly flows into reservoirs and hourly volumes of water pumped.

3. It computes volumes and costs of actual and expected spillages and the penalties incurred when reservoirs operate at low levels.

4. Computes, in units of energy, the cost of activating and operating pumping units under predetermined policies.

5. It computes the benefit or cost of changes between initial and end state volumes in the system.

With the aid of the above characteristics we are enabled:

1. To choose the optimal set of policies satisfying given requirements.

2. To determine the maximum withdrawal at Eshkol which the system can supply while satisfying the required constraints.

3. To determine the ideal energy tariff restrictions in order to supply increased withdrawals.

THE ECONOMIC MODEL

The cost function considered is the sum of all costs, (expressed in energy units), resulting from the operation of the system for one week under a given policy. Costs which do not vary with, or depend on, the operating policy are not included. A period of one week is stipulated due to the weekly relaxation of tariff restraints specific to the 40 hours around the Sabbath.

The constituents of the cost function are:

COST = Energy required to operate the K.N.T. and ZALMON pumping station

+ Energy losses due to the operation of Eshkol reservoir at levels lower than the maximum

+ Energy losses due to expected spillage at ESHKOL reservoir

+ Energy losses due to expected spillage at ZALMON reservoir

+ Cost of activation of pumps not in operation.

Expected spillage refers to amounts of water which would be expected to spill when,

1. The total of reservoir and canal volumes exceeds the maximum reservoir volume and.

2. A total power failure occurs.

The expected spillage takes into consideration the above two factors as well as the known probability distributions of power failure durations, and the probability of a failure occurring during any particular hour.

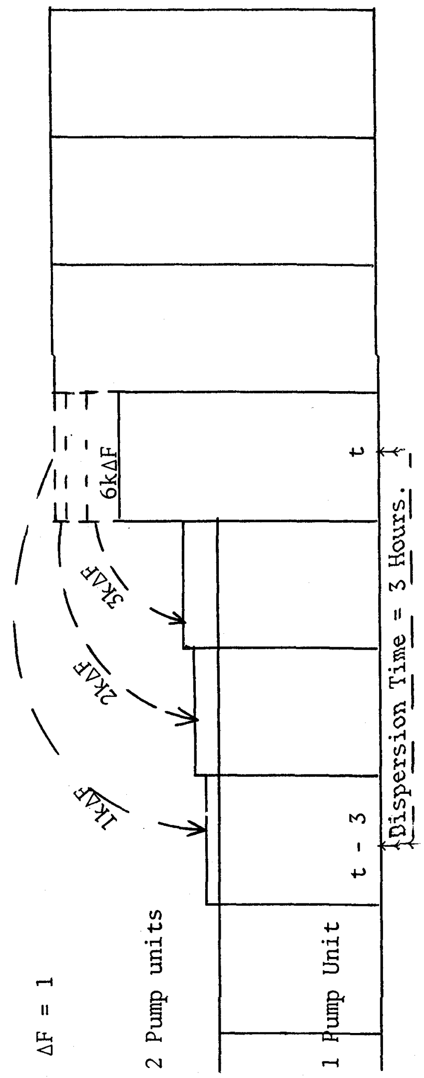
THE HYDRAULIC SIMULATOR

In order faithfully to simulate the behaviour of the whole system a method was required whereby the flow of water from a canal, caused by continuously changing inflows, could be approximated. Canal flows differ from flows in closed conduits in the following ways:

- change in outflow from the canal lag behind changes in inflow,
- the outflow at any instant of time is influenced by the distribution of inflows over a certain period of time prior to that instant,
- the volume of water stored in the canal varies with time and changes of inflow,
- water having once been introduced into the canal, the flow cannot be stopped or altered by outside influence,
- a change in an existing inflow is noticed at the outlet after a period of lag which is less than the time taken for water to traverse an empty canal.

Nature of the Simulator

From the logbooks of the system which are updated hourly,



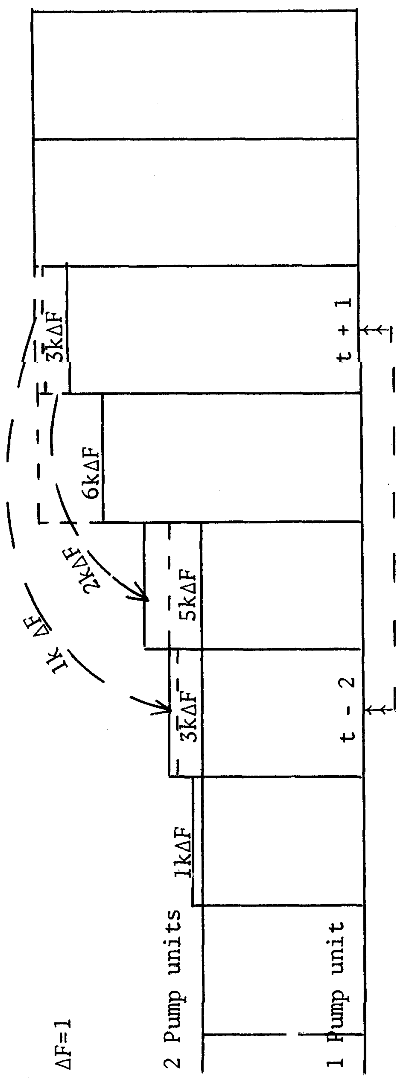
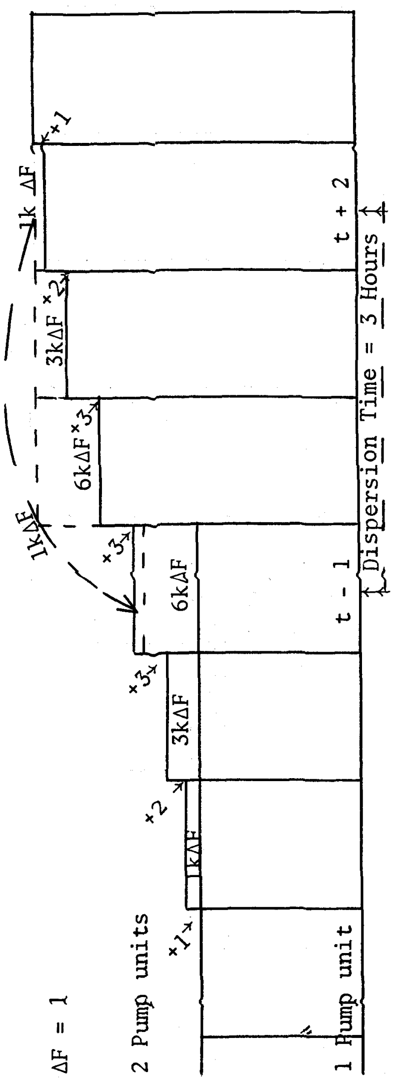


Figure 3 : The Dispersion of a Wave Front ΔF=1 to the Preceeding Three Hours' Flow, at Time t .

Figure 4 : The Dispersion at Time (t+1) .



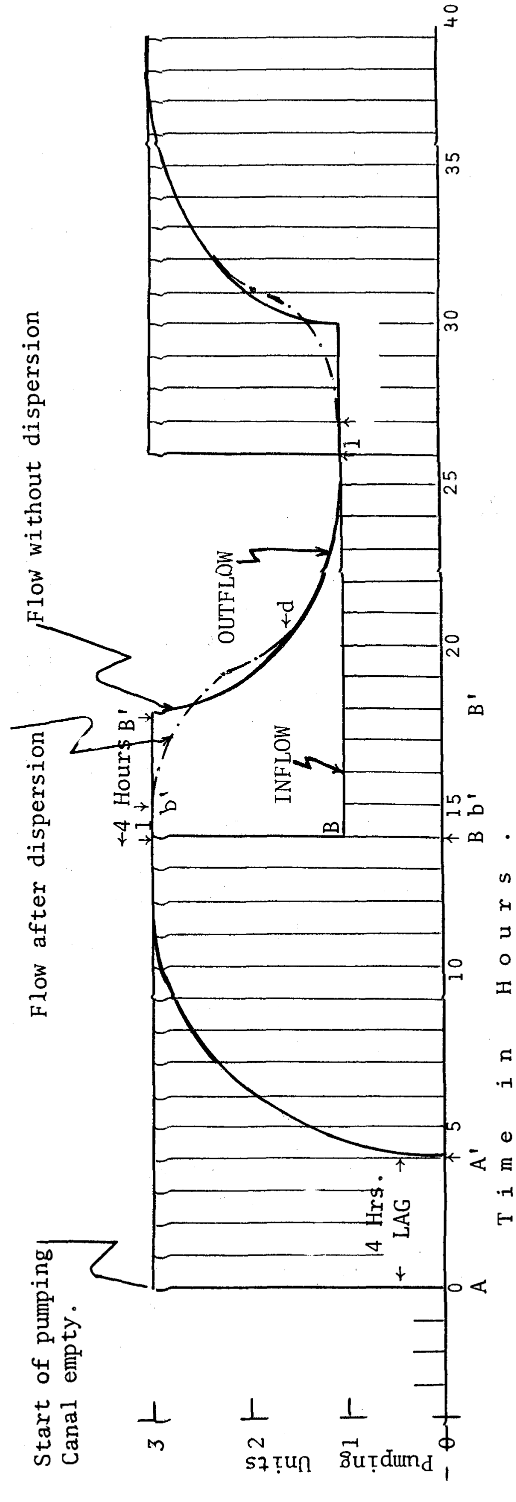


Figure 5 : The Dispersion at Time (t+2) .

Figure 6 : Inflow and Outflow in a Canal - (Schematic).

data of hourly flows into and out of canals and reservoirs, as well as elevations of reservoirs were collected for periods of a week at a time.

The data concerning the activations of pumping units (inflows to canals) were plotted as well as the outflows of water from the canals (obtained from changes in reservoir elevations).

The nature of the curves representing outflows were examined in contrast with the stepped lines representing discrete pump activations.

As a result of this comparison the following empirical concepts were developed viz. Lag, Distortion and Dispersion.

Lag

The first sign of a flow at the outlet of the canal due to the introduction of a new wave (a discrete flow of water introduced at a certain instant i.e. the flow from, say, a configuration of three pumps) into the empty canal, appeared after a lag of about four hours.

Distortion

The curve of the increase in outflow was seen to be exponential, asymptotic to the value of the flow being introduced into the canal.

Dispersion

New waves introduced over existing flows produced initial changes in the outflow after a pause of about one hour, i.e. much less than four hours of lag time. The change was mainly in the initial part of the exponential curve, whereafter the curve matched the curve of an initial wave. This is due to the fact that a new wave rides on an existing flow thus dispersing itself forward in space.

Simulation of Lag, Distortion and Dispersion

Lag is easily determined by measuring the time lapse either in the field or from plotted graphs of historical data. Each hourly flow is then dealt with after the elapse of the lag time.

The method finally adopted to simulate distortion can be simply represented physically by means of a container of uniform cross-sectional area and into which flows, Q, are introduced.

An outlet allows an outflow of q which is proportional to the height H of the fluid in the container, i.e. q=F.H.. This is an arbitrarily assumed relation and is certainly not true hydraucally.

$$dq = F.dH = [\frac{Q-q(t)}{\alpha}]dt \qquad \text{(eq. 1)}$$

The solution obtained is

$$q(t) = q - [Q-q(o)]\ e^{-\frac{F}{\alpha}t} \qquad \text{(eq. 2)}$$

The volume of water flowing out of the distorter during one time unit is:-

$$V = Q + \frac{\alpha}{F}[Q-q(t_o)]\ [e^{-\frac{F}{\alpha}} - 1] \qquad \text{(eq. 3)}$$

and the volume of fluid currently in the distorter is:

$$Vd = H(t) = \frac{\alpha}{F}\ q(t) \qquad \text{(eq. 4)}$$

The "alpha parameter" $\frac{\alpha}{F}$ is dimensionless and calibrated with the aid of historical data.

The dispersion of a new wave front is achieved by transferring parts of itself three, two and one hours forward in time. The amount transferred is directly proportional to the difference in wave sizes and inversely to the time difference. If ΔW is the difference in wave height then the amount transferred are 1.K. ΔW, 2.K. ΔW and 3.K. ΔW, where K is a transference factor so chosen as to ensure an evenly disposed wave front. It is algorithmically computed as:

$1/K = (1 + \text{Dispersion Time})^2 - 1$. In our case the Dispersion Time = 3 and $1/K = (1+3)^2 - 1 = 15$.

The value of the dispersion time can easily be determined from the historical data by measuring the time elapsed until the first reaction to a new wave is detected (R.T.). Dispersion time = Lag Time = R.T. = 3 hours for this system.

Case No.	Description of Tests Cases
11	45,000 m^3/hr withdrawal.Basic Case
12	30,000 m^3/hr withdrawal
13	40,000 m^3/hr withdrawal
14	50,000 m^3/hr withdrawal
15	55,000 m^3/hr withdrawal
15'	55,000 m^3/hr withdrawal 15 Continued for another week
16	60,000 m^3/hr withdrawal
16'	60,000 m^3/hr withdrawal 15 Continued for another week
17	35,000 m^3/hr withdrawal
20	30,000 m^3/hr withdrawal 2 Pumps Deactivated Stable
21	45,000 m^3/hr withdrawal 1 Pump Deactivated KNT Not Stable
22	45,000 m^3/hr withdrawal 1 Pump Deactivated ZALMON Not Stable
23	45,000 m^3/hr withdrawal 2 Pumps Deactivated Not Stable
24	40,000 m^3/hr withdrawal 1 Pump Deactivated KNT Stable
25	40,000 m^3/hr withdrawal 1 Pump Deactivated ZALMON Stable
26	40,000 m^3/hr withdrawal 2 Pumps Deactivated Stable
27	35,000 m^3/hr withdrawal 2 Pumps Deactivated Stable
28	45,000 m^3/hr withdrawal 2 Pumps Deactivated + 4 hrs Extra Stable
31	Basic Case
32	Pump Deactivated - Rapid Reduction
33	Set Points

Case No.	Description of Tests Cases
34	Set Points - Slow Reduction
35	Set Points - Slow Reduction
36	Set Points - Slow Reduction
37	Set Points - Slow Reduction
38	45,000 m^3/hr withdrawal 2 Pumps Deactivated + All pumps on Saturday.
41-46	Tests of varying danger margins.

As a basis for comparison a "basic case" was defined so as to reflect accurately conditions ruling in the physical system at the time. This case was tested, flows and levels printed out and the operating cost, in accordance with the cost function, evaluated.

EFFECTIVENESS OF POLICIES

The specification of danger margins is of practical use only when withdrawals are in the vicinity of 50,000 m^3/hr. The policy would certainly offer benefits at rates of withdrawals around 40,000 m^3/hr, but alternative policies exist which offer even larger benefits.

Set Points

Some saving is achieved by stipulating varying set points at withdrawal rates of 45,000 m^3/hr, but their main advantage is to achieve predetermined levels at fixed times. They may lead to results preferable to the application of danger margins but do not lead to optimal results.

Maximum Configuration Restrictions

This series of tests ("2" series) leads to the greatest number of preferred and optimal policies. (An optimal policy is that policy which cannot be improved upon. A preferred policy is the best of a number of known alternate policies).

By limiting operation of pumps to a maximum of configuration II it is possible to avoid the relatively large increase in energy consumption per m^3 pumped that occurs when three pumps work together. This is true for both stations, though more especially for K.N.T. station.

Configuration	Energy Cost Kw-hrs/m^3	K.N.T.-209.5 Difference	Energy Cost Kw-hrs/m^3	ZALMON+37.71m Difference
I	0.8017		0.3488	
		0.0058		0.0064
II	0.8075		0.3552	
		0.0147		0.0077
III	0.8222		0.3629	

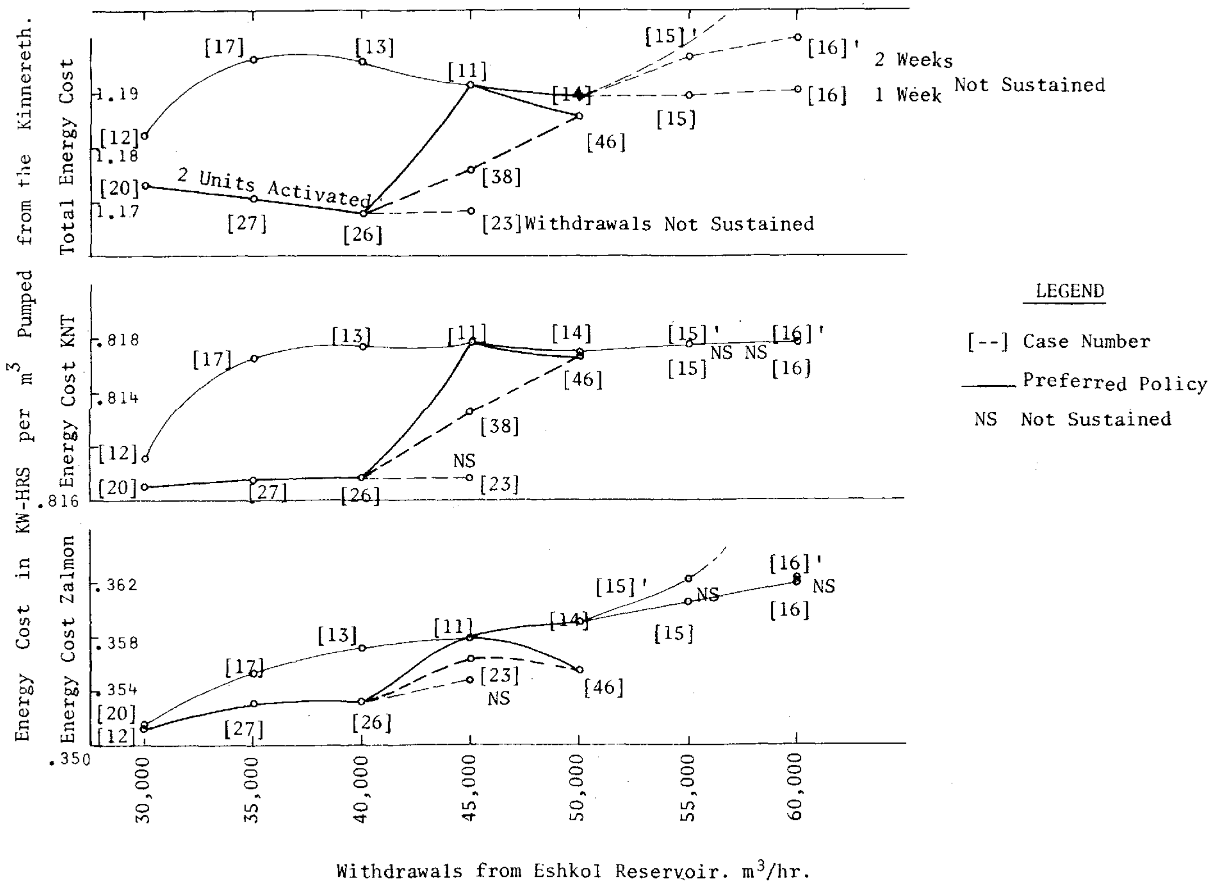


Figure 7 : Reactions to increased Withdrawals at present Tariff Constraints.

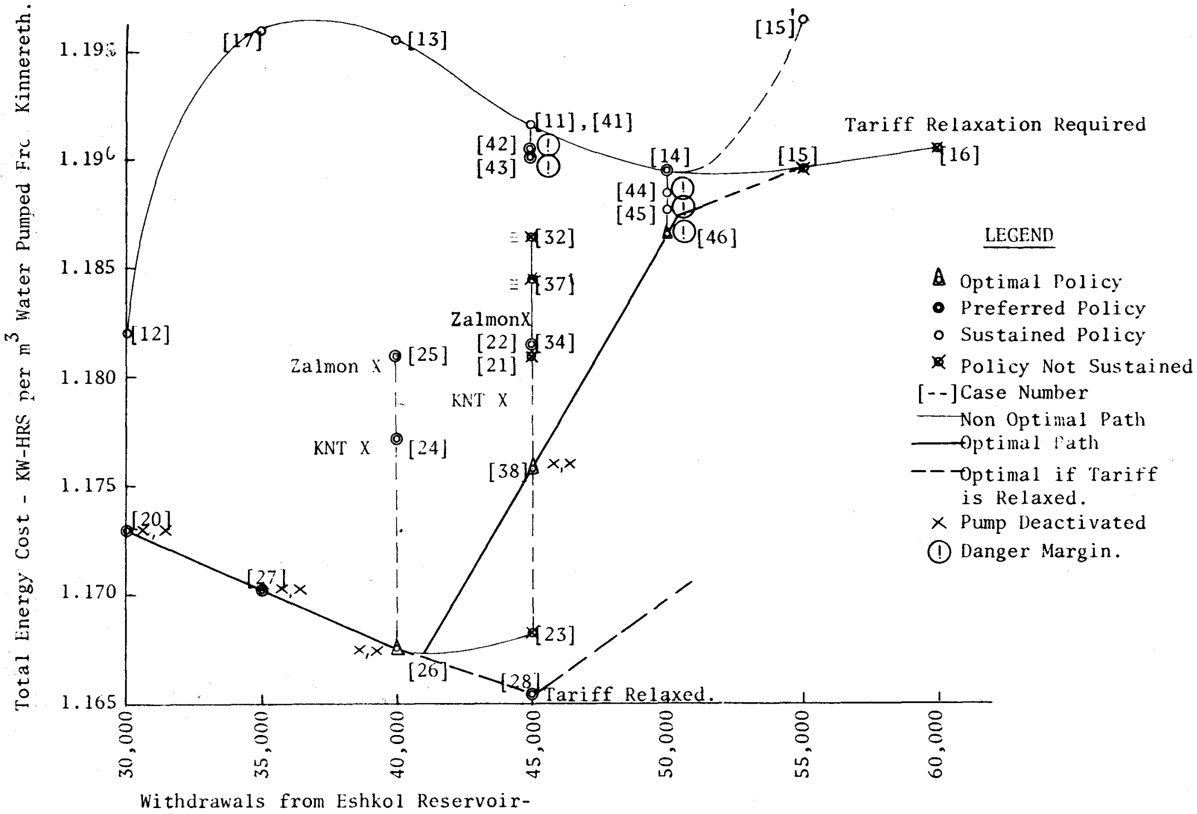


Figure 8 : Optimal Policy Path for Varying Withdrawals from Eshkol Reservoir.

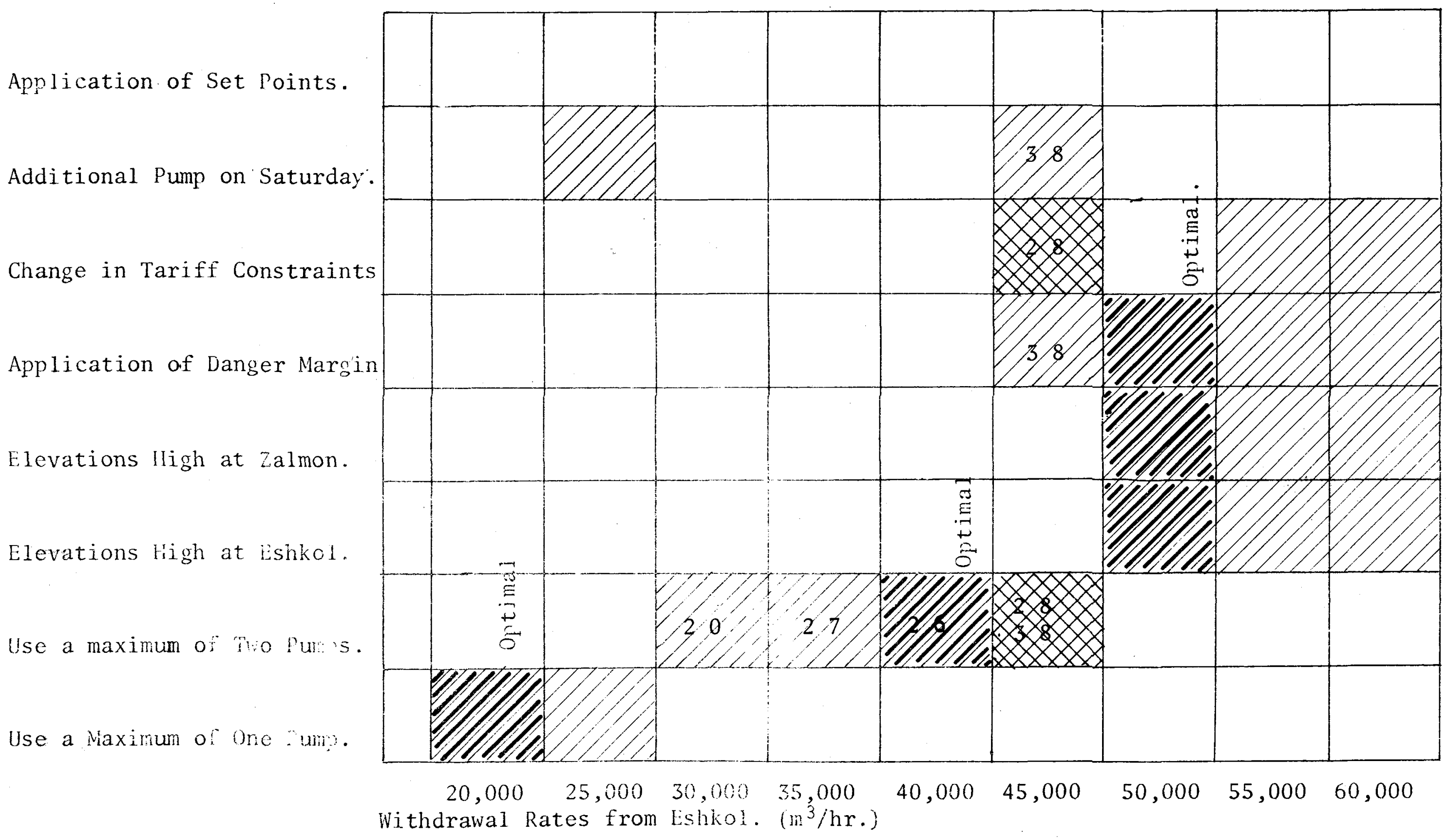


Figure 9 : Choice of the Suitable Policy at Varying Withdrawal Rates from Eshkol Reservoir.

Tariff Relaxation

Considerable savings are potentially attainable (case 28, 45,000 m^3/hr) with a relaxation of tariff restrictions. Under this policy it is possible to supply water at an even lower total energy cost per m^3 than case 26 which is optimal at 40,000 m^3/hr.

It is clear that withdrawal rates of 55,000 m^3/hr and above can only be met with the aid of tariff relaxation.