An Economic Model for Irrigation Well Management in a Declining Aquifer

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A computerized model is developed that uses the aquifer characteristics and irrigation requirements to estimate hydraulic properties of a well pumping from an unconfined aquifer with a steadily declining water table. The model simulates electrically-powered well operation under the most economical conditions. High versatility of model inputs allows examination of many facets of well management. One example is the effect of electricity price on the ratio of energy cost to total cost of supplying water at different average total heads. At current electricity prices, energy accounted for 65 to 70 percent of total water costs. In a second example, as average annual efficiency decreased, average annual cost per acre-foot increased and average annual pumping volume decreased, leaving average annual total energy costs almost constant.

The operation of a well in a declining aquifer is frequently based on decisions which assume a static water table. To maintain a given pumping volume range and corresponding economic efficiencies, the well system must be changed as the water table declines. Minimization of the well system cost can occur only when future aquifer conditions, well characteristics, and current and future cost alternatives can be estimated. To facilitate this decision-making process, a computer model similar to Feldman and Whittlesey was developed. The model relies on hydraulic principles to determine drawdown, pumping and well characteristics. These hydraulic principles were derived from equations presented by De Wiest (p. 243) and are applicable to a steadily declining, unconfined aquifer. The model combines physical, hydrologic, and engineering relations with economic principles to provide a temporal least-cost well system without consideration of water value. It is a model that simultaneously considers all the physical and economic factors of the well system in a dynamic setting. This paper presents the basic operation of the model including input data, the decision-making process, output, and examples of model use.

The Model

Input

Model inputs can be divided into economic considerations, aquifer characteristics, and well system characteristics. Input data requested by the computer, and the operator's reply are shown in Table 1. The maintenance ratio presented in Table 1 is based on an operating time of 100 days at 22 hours per day, and is adjusted according to the number of days the well actually operates. Current cost data built into the model, but subject to change, include: (1) cost of drilling the well, including the test holes; (2) bowl cost data by types, with efficiencies and operating characteristics; (3) cost of electric motors with corresponding operating panels, and cost to rewind the motor; (4) cost of column pipe; and (5) cost to go in and out of the well for repair purposes.

Well Design

The model uses the input data to design

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TABLE 1. Example of input data for the irrigation well model.

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1. Economic Considerations
   ANNUAL INTEREST RATE IN PERCENT? 10
   ANNUAL TAX & INSURANCE RATE IN PERCENT? 2
   COST OF ELECTRICITY IN $/KWH? .010
   WHAT ARE THE MAINTENANCE RATIOS FOR:
     PARTWIND PANEL? .021
     BOWLS? .014
     MOTOR? .021
     COLUMN PIPE? .014
     DISCHARGE ASSEMBLY? .014
     HOLE AND CASING? .0042
   INPUT THE TIME IN YEARS TO A CONSTANT SALVAGE RATIO, AND THE SALVAGE RATIO FOR:
     PARTWIND PANEL? 20 , .1
     BOWLS? 22 , .1
     MOTOR? 24 , .2
     COLUMN PIPE? 20 , .05
     DISCHARGE ASSEMBLY? 20 , .05
     HOLE? 30 , 0
2. Aquifer Characteristics
   HYDRAULIC CONDUCTIVITY IN FEED/DAY? 20
   SATURATED THICKNESS IN FEED? 180
   DEPTH FROM SURFACE TO BOTTOM OF AQUIFER IN FEET? 440
   WATER TABLE DECLINE IN FT/YR? 3
   REQUIRED SURFACE HEAD IN FEET? 20
3. Well Characteristics
   DIAMETER OF BOREHOLE IN INCHES? 24
   MAXIMUM PUMPING RATE IN GAL/MIN? 800
   NUMBER OF DAYS/YEAR FOR PUMPING? 140
   MOTOR EFFICIENCY IN PERCENT? 90
   EXPECTED LIFE OF BOWLS IN YEARS? 22
   ARE BOWLS ON A REPAIR SCHEDULE, (Y = YES, N = NO)? Y
   REPAIR INTERVAL FOR BOWLS IN YEARS? 11
   WHAT IS THE LOSS IN SYSTEM EFFICIENCY PER YEAR IN PERCENT:
     DUE TO MOTOR WEAR? 0
     DUE TO BOWL WEAR? 0
   ARE BOWLS TO BE SET AT BOTTOM OF AQUIFER ( Y = YES, N= NO)? N
```

the well and calculate its initial cost. The computer printout of input data, the initial factors calculated for well operation, and well cost are shown in Table 2. Combining the aquifer and well characteristics, the model calculates the depth at which to set the bowls through use of hydraulic principles. Using hydraulic equations, the initial drawdown and associated total dynamic head (TDH) are estimated at the maximum pumping rate. The type and number of bowls are determined by using a table designed from pump curves. A pump curve is the pumping rate plotted against head, with the horsepower required and efficiency of the bowls superimposed. Using the selected bowl, a second table is entered to determine bowl cost and efficiency. The head and pumping rate are converted to horsepower which is adjusted according to bowl and motor efficiencies to determine the working horsepower. A table of motor horsepower and cost is entered to select the motor. The head that would exceed bowl design and the time in years to reach this head are estimated. The minimum saturated thickness from which the minimum rate could be pumped is also estimated.

TABLE 2. Example computer printout of input data and well cost.

```
ANNUAL INTEREST RATE IS 10%
ANNUAL TAX & INSURANCE RATE IS 2%
COST OF ELECTRICITY IS $0.0100 PER KWH
HYDRAULIC CONDUCTIVITY IS 20.00 FEET/DAY
SURFACE HEAD IS 20 FEET
DIAMETER OF THE BOREHOLE IS 24 INCHES
DISTANCE FROM SURFACE TO BEDROCK IS 440 FEET
INITIAL SATURATED THICKNESS IS 180 FEET
BOWLS WILL BE SET AT 110 FEET BELOW THE STATIC WATER LEVEL (SWL)*
INITIAL TOTAL DYNAMIC HEAD (TDH) IS 335 FEET*
INITIAL DRAWDOWN IS ESTIMATED TO BE 55 FEET*
WATER TABLE DECLINE IS 3 FT/YR
ALLOWABLE PUMPING RATES IN GAL/MIN ARE:
  800 FOR THE MAXIMUM
  600 FOR THE MINIMUM*
NUMBER OF PUMPING DAYS/YEAR IS 140
EXPECTED LIFE OF THE BOWLS IS 22 YEARS
BOWLS ARE ON A REPAIR SCHEDULE OF 11 YEARS
EFFICIENCY LOSS PER YEAR RESULTING FROM WEAR IS
  0.00% DUE TO THE ENGINE
  0.00% DUE TO THE BOWLS
  0.00% TOTAL
SYSTEM WILL BE INEFFICIENT TO OPERATE WHEN THE SATURATED THICKNESS REACHES
  114 FEET*

INITIAL COST*
HOLE                      $     11880.00
COLUMN PIPE               $     10064.00
DISCHARGE ASSEMBLY                789.00
BOWLS                     $      2603.00
MOTOR                     $      2687.00
PARTWIND PANEL            $      2165.00
TOTAL                     $     30188.00

MOTOR H.P. IS*           100
INITIAL EFFICIENCIES ARE:*
  MOTOR  90%
  BOWL   75.3%
  TOTAL  67.77%
INITIAL WORKING H.P. IS 99*
  8 BOWLS OF TYPE 6*
TIME UNTIL TOTAL DYNAMIC HEAD EXCEEDS BOWL DESIGN IS 21 YEARS*

                      MAINTENANCE*      TIME TO CONSTANT     SALVAGE
   ITEM                  RATIO           SALVAGE VALUE        RATIO
   PANEL                 0.029                20              0.100
   BOWLS                 0.019                22              0.100
   MOTOR                 0.029                24              0.200
   COL. PIPE             0.019                20              0.050
   DIS. ASSEMBLY         0.019                20              0.050
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*Initial factors calculated for well operation

Operation

At the end of each year, the model prints out the total and current year values for capital investment, depreciation, tax-interest-insurance, maintenance, the salvage value, current year's energy cost, total cost, acre-feet pumped, annual cost per acre-foot, and average and variable cost per acre-foot (Table

3). All capital investment items, except the well, are depreciated by the sum of the years digits method. The well is depreciated by the straight line methods. The saturated thickness and depth of pump bowls below the static water level are reduced by the average annual water table decline at the end of each year. The system efficiency is reduced by the amount specified in the input, and by an amount determined by the pumping curves. The latter is 0.02 percent per gallon reduction in pumping from the designed maximum rate. Pumping rate is reduced because the pumping curves dictate a near constant working horsepower over all heads; thus, as head increases, pumping rate must decrease.

From these new aquifer-well conditions, a new drawdown, pumping rate, and total dynamic head are calculated using hydraulic equations. The aquifer-well conditions and age of the well components are examined to determine if any basic decision points were reached during the year. A basic decision point is reached when conditions due to hydraulic characteristics or age of the system require an expenditure. Each decision point may involve several alternative decisions but is affected by a specific set of conditions. Six basic decision points generated by the model that require separate lines of action are: 1) Motor repair or replacement time; 2) Pumping rate or head not within design; 3) Pump bowl repair time; 4) Pump bowl replacement time; 5) Drawdown within 20 feet of the pump bowls; and 6) Saturated thickness too thin.

The decision at each of these points is based on hydraulic limitations and alternative investment opportunities over some period of time.

The decision points depend on the well system, and not on the value of water being pumped. No assumptions are made as to the value-in-use of the water. It will always be mandatory to maintain the well system within the physical limits set by input data, and the selection of a least-cost investment opportunity will apply only to the purchase or maintenance of equipment to maintain the well system within these limits.

Economic Decision Criterion

As each decision point occurs during well operation, the model compares investment alternatives and selects the least-cost investment opportunity consistent with well design. An investment alternative exists when an expenditure at the decision point will delay or eliminate an expenditure at some future point in time. For example, at the time the pump bowls are in need of repair, the model considers two other investment alternatives: (1) repair the old and add additional pump bowls, or (2) purchase a new set of bowls. These investment alternatives will delay or eliminate similar expenditures at the future decision point 2. The model scans forward in time to locate this decision point and calculates its cost, then compares the net future value of each of the current investment opportunities at a specified interest rate. The net future value is calculated as follows:

$$1) \qquad NFV = C_n\,(1 + i)^t - C_L$$

where NFV = net future value; C_n = value of current investment alternatives; i = interest rate reflecting opportunity cost rate; t = time in years to next decision point; and C_L = investment required at next decision point (cost later).

The largest negative NFV for the current investment alternatives would show that investment to be the least costly. If neither NFV is negative, the pump bowls are repaired only.

Investment decisions frequently involve an additional cash outlay at present to eliminate an added cost a few years from now. For example, a motor must be purchased now for \$2500, but a larger motor will be needed 3 years later and would cost \$1200 with trade-in of a 3-year old motor. However, the larger motor could be purchased at present for \$3000, or an additional \$500. Therefore, the \$500 is the investment alternative to eliminate a \$1200 investment 3 years later. Using Equation 1) and assuming an interest rate that reflects an opportunity cost rate of 10 percent, the decision-criterion would be:

$$NFV = \$500(1 + 0.1)^3 - \$1200 = -\$534.50$$

TABLE 3. Example computer printout of yearly cost and decision points.

YEAR	TOT CAP INV	SALV VAL	TOT DEP	YRS DEP	TOT TAX INT	YRS TAX INT	TOT MAIN	YRS MAIN	YRS CAP INV.	YRS ENGY	SUM YRS COST	ACRE FEET	YRS $ AC-FT	AVE $ AC-FT	VAR $ AC-FT
1	30188	28248	1939	1939	3506	3506	476	476	0	2286	8208	452	18.12	18.12	6.10
2	30188	26384	3803	1864	6784	3277	952	476	0	2286	7905	447	17.64	17.88	6.16
3	30188	24594	5593	1789	9842	3058	1428	476	0	2286	7611	442	17.20	17.66	6.24
4	30188	22880	7307	1714	12691	2848	1904	476	0	2286	7326	436	16.78	17.44	6.32
5	30188	21240	8947	1639	15338	2647	2381	476	0	2286	7049	430	16.36	17.23	6.41
6	30188	19674	10513	1565	17793	2454	2857	476	0	2286	6782	425	15.94	17.02	6.49
7	30188	18184	12003	1490	20065	2271	3333	476	0	2286	6524	419	15.54	16.82	6.58
8	30188	16768	13419	1415	22162	2097	3809	476	0	2286	6275	414	15.14	16.62	6.66
9	30188	15428	14759	1340	24094	1931	4286	476	0	2286	6035	408	14.75	16.42	6.75
10	30188	14162	16025	1265	25869	1775	4762	476	0	2286	5804	403	14.38	16.23	6.84
BOWL REPAIR TIME BOWL REPAIR COST $ 1550															
THE DRAWDOWN IS WITHIN 20 FEET OF THE BOWLS THE BOWLS HAVE BEEN LOWERED 40 FEET, COST $ 1088 + $ 210 = $ 1298															
11	31276	13960	17315	1289	27622	1752	7019	2257	1088	2286	7586	405	18.68	16.44	11.19
REWIND TIME, LARGER MOTOR NOW OR REWIND NOW AND LARGER MOTOR AT TDH]D LARGER MOTOR NOT NEEDED AT TDH]D MOTOR REWOUND FOR $ 800															
12	31276	12750	18525	1209	29224	1602	8317	1297	0	2286	6396	394	16.22	16.42	9.09
13	31276	11620	19655	1130	30687	1462	8815	497	0	2286	5376	387	13.86	16.24	7.17
14	31276	10569	20706	1050	32018	1331	9312	497	0	2286	5165	382	13.50	16.06	7.28
15	31276	8599	21676	970	33228	1210	9810	497	0	2286	4964	377	13.16	15.89	7.38
16	31276	8708	22567	891	34327	1098	10307	497	0	2286	4773	371	12.83	15.72	7.48
17	31276	7896	23379	811	35323	996	10805	497	0	2286	4591	366	12.53	15.55	7.59

(continued)

TABLE 3. (continued)

YEAR	TOT CAP INV	SALV VAL	TOT DEP	YRS DEP	TOT TAX INT	YRS TAX INT	TOT MAIN	YRS MAIN	YRS CAP INV	SUM YRS ENGY	SUM YRS COST	ACRE FEET	YRS $ AC-FT	AVE $ AC-FT	VAR $ AC-FT
IT IS 5 YR TO MIN. SAT. THICK. PUMPING WILL CONTINUE WITHOUT REQUIRED REPAIRS OR REPLACEMENTS															
18	31276	7165	24110	731	36227	903	11302	497	0	2286	4419	361	12.24	15.39	7.71
19	31276	6513	24762	651	37047	820	11800	497	0	2286	4259	355	11.97	15.23	7.83
THE DRAWDOWN IS WITHIN 20 FEET OF THE BOWLS THE BOWLS HAVE BEEN LOWERED 30 FEET, COST $ 816 + $ 195 = $ 1011															
20	32092	6683	25408	645	37888	840	12509	708	816	2286	4481	349	12.81	15.12	8.56

TDH]D, PUMPING TERMINATED

TOTAL CAPITAL INVESTMENT $ 32092.00

TOTAL MAINT., REPAIR COST $ 12509.05
TOTAL ENERGY COST $ 45730.44
TOTAL DEPRECIATION $ 25408.44
TOTAL TAX INT. AND INS. $ 37888.68

Since the net future value is a negative \$534.50, the larger motor would be purchased now. Investment alternatives occur throughout the well model operation and will be discussed by decision points.

Occasionally, motor investment alternatives may occur between two decision points affecting pump bowls. This may occur during decisions points 2 or 3 when all of the following conditions exist: 1) the motor needed at the later pump bowl decision point is larger than the motor needed now; 2) the life of the motor expires or the motor needs repairing before the later pump bowl decision; and 3) the criterion in decision point 1 shows the least-cost alternative would be to purchase a larger motor when the motor needs repairing or motor life expires. If all of these conditions are met, an alternative net future value is calculated as follows:

$$3) \qquad NFV = C_n(1 + i)^{t_1} + (C_n - M)(1 + i)^{(t - t_1)} - C_L$$

where M = cost of larger motor at motor replacement (repair time) and t_1 = time to motor replacement (repair)

Decision Points

1. Motor repair or replacement time

The repair interval and expected life of the motor were inputs into the model. When the motor reaches an age when repair or replacement is required, the model follows the flow diagram presented in Figure 1. An investment opportunity does not exist unless a larger motor would be needed at the next decision point. In the case of motor repair, the investment alternative is the cost of the larger motor now less the cost of motor repair; and in the case of motor replacement, the investment alternative is the cost of the larger motor now less the cost of the current size motor.

In the printout example in Table 3, the motor repair decision point falls in Year 12. The computer prints out "Rewind time, larger motor now or rewind now and larger motor at TDH > D" (*T*otal *D*ynamic *H*ead exceeds *D*esign). In this case, the model determined that, when the system is redesigned at the time total dynamic head exceeds design, a larger motor will not be needed. Therefore, since there is no investment opportunity, the decision was made to rewind the motor.

2. Pumping rate or head not within design.

This decision point is reached when the pumping rate falls below 75 percent of the designed maximum rate, or when the total dynamic head becomes greater than that designed for the pump bowls. Under most conditions, the latter will occur first, but in either case, the objective is to obtain a pumping rate near the designed maximum. The alternative investment is the difference in cost of adding one or more pump bowls to compensate for the increased head, and the cost of replacing the pump bowls with a new set that will match the new head. The purchase of a new set of pump bowls now would eliminate this purchase at decision point 3, pump bowl replacement time.

The decision-making process used to determine the best alternative investment is described in Figure 2. The cost of adding or purchasing a new set of pump bowls may include the cost of lowering them and of purchasing a larger motor and electrical control panel. The cost of adding one or more pump bowls may also include the cost of repairing the old ones. The entire cost of adding or replacing the pump bowls is used in determining the best investment alternative. If the NFV is negative, the old pump bowls are exchanged for a new set at the current salvage value; otherwise, additional pump bowls will be added to the old set. The additional pump bowls are immediately depreciated to the same value of the existing ones because pump bowls added to a system have no more salvage value than the old ones.

The model assumes that adding a bowl is impossible if the drawdown is within 25 feet of the pump bowls and they are set on the bottom of the aquifer. In this case, the model will try to replace the bowls by reducing the maximum pumping rate and thus decrease

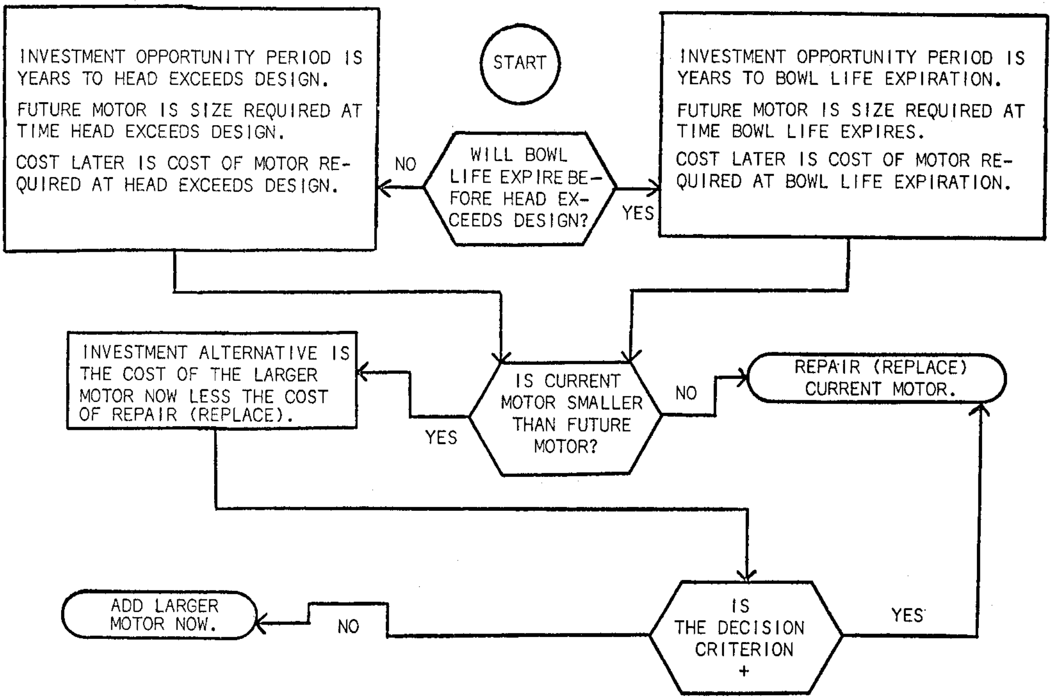

Figure 1. Flow diagram for Decision Point 1, motor repair or replacement time.

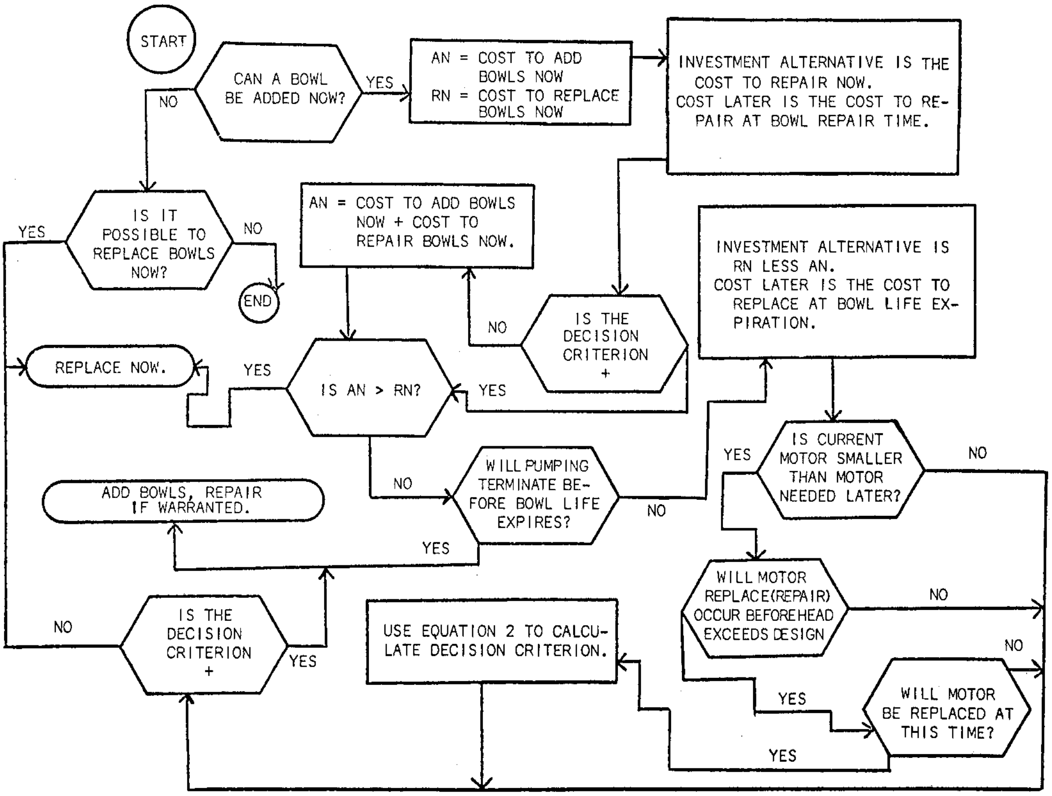

Figure 2. Flow diagram for Decision Point 2, rate or head not within design.

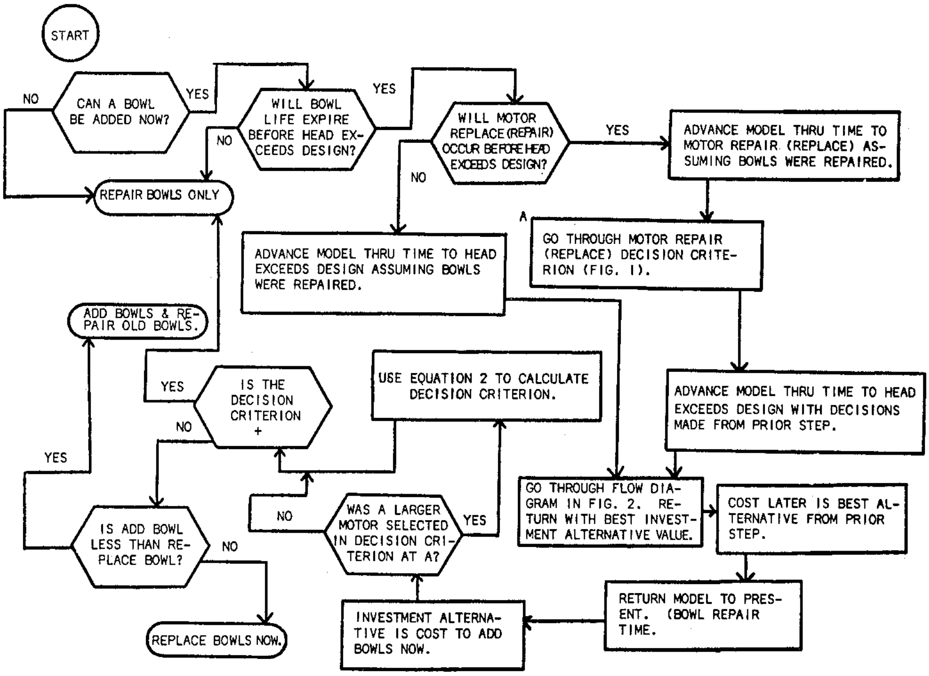

Figure 3. Flow diagram for Decision Point 3, bowl repair time.

drawdown. If this reduced pumping rate is less than the minimum designed rate, the model terminates pumping.

3. Pump bowl repair time

The decision point for pump bowl repair time is determined by input data. An investment opportunity will exist only if a bowl can be added at repair time without exceeding the designed rate, and if total dynamic head exceeds design before bowl life expires. The investment alternatives were discussed as an example under Economic Decision Criterion. The decision-making process at this decision point is described in Figure 3. It is very complicated and includes the criterion of decision points 1 and 2 (Figures 1 and 2). The cost to add or purchase a new set of pump bowls now or when pumping rate or head are not within design may include the cost of a new motor and control panel to meet the added power requirement. The least-cost investment alternative is the largest negative NFV for adding pump bowls or purchasing a new set. If neither NFV is negative, the bowls are repaired only.

4. Pump bowl replacement time.

At this decision point, an investment opportunity does not exist, and a new set of pump bowls must be purchased. The type and number of bowls purchased depend on the total dynamic head and drawdown, and are selected to return pumping to near the maximum designed rate. If the saturated thickness is insufficient for this rate, the model will attempt to select pump bowls that will produce a rate greater than the minimum designed rate. If this selection is impossible, pumping will terminate.

5. Drawdown within 20 feet of the pump bowls.

When the drawdown is within 20 feet of the bowls, the pump may suck air and operate very inefficiently. This 20-foot factor is used as a safety zone to compensate for uncertainties in well efficiencies or inaccuracies of the hydraulic estimates. When this point is reached, the distance that the pump bowls are lowered is determined by the product of the average annual water table decline and the replacement interval of the pump bowls. This distance is rather unimportant to the overall operation and economic results of the model so long as the distance is not so great that a large sum becomes tied up in column pipe before it is necessary. In such a case, the interest, insurance, taxes, and maintenance costs become significant.

6. Saturated thickness too thin.

As the water table drops, the saturated thickness will eventually reach a point where pumping at the minimum designed rate will not be possible. This point will occur when the pump bowls are set on the bedrock, and the drawdown is within 20 feet of the bowls. This point was chosen due to unknown efficiencies in the well at a lesser saturated thickness and an unpredictable bedrock surface. Therefore, pumping is terminated due to physical limitations and not economical considerations.

Examples of Model Use

The model is highly versatile due to the large number of inputs available. The variable input will allow: (1) changing economic factors to examine their effects on costs, (2) changing efficiency factors to examine their effects on pumping rates and costs, and (3) changing the well or aquifer characteristics to examine their effects on any of the model's outputs.

An example of changing an input and its effect on model output is the effect of the price of electricity on the ratio of energy cost to total cost. The model was set up identical to the data of Table 2 and the program was run to completion, as shown in Table 3. The total energy cost for the 20-year period was subtracted from the total lifetime cost. The resulting sum was the total non-energy cost, which was assumed constant regardless of the price of electricity. Using this data, an equation was developed that would calculate the total lifetime cost regardless of the price of electricity. This equation is:

$$3) \qquad T_{LC} = E_C \times ¢/kWh + N_{EC}$$

where T_{LC} = total lifetime cost in dollars; E_C = energy cost at 1¢/kWh; ¢/kWh = price of electricity in cents per kilowatt-hour; and N_{EC} = non-energy cost.

Thus, the relationship (R) between energy (electricity) cost and total cost can be derived from the ratio:

$$4) \qquad R = \frac{E_C \times ¢/kWh}{T_{LC}}$$

Three ratio curves were developed from the model by using distances from the surface to bottom of aquifer of 340, 440, and 540 feet, with a saturated thickness of 180 feet. These figures essentially change the average total dynamic head by 100-foot increments. Electricity cost to total cost ratios as a function of the price of electricity are shown in Figure 4. If electricity prices exceed about $0.02/kWh, the cost of electricity is greater than all other costs. The range of well conditions used in the examples include most wells of the Texas High Plains. The current price of electricity for this area is $0.036/kWh. Therefore, about 65 to 70 percent of the total operating cost is for electricity. The important point of Figure 4 is that energy cost is the dominant factor in pumping water on the Texas High Plains, not the cost of the well.

A second example of changing input and its effect on model output is the effect of total system efficiency on average annual water cost and average annual pumping volume. The model was again specified with the data of Table 2, and the program was allowed to estimate 10 years of operation. The initial total system efficiency was varied by adjusting the initial motor efficiency in nine increments of 5 percent each. This procedure in effect produced nine average system efficiencies that ranged from 76 to 45 percent.

For each run, the average annual system efficiency, electricity cost per acre-foot of water pumped, and the total acre-feet pumped were calculated. These data are plotted in Figure 5. The increase in water cost per acre-foot and decrease in pumping volume, are not linearly related with the decrease in efficiency. A 2 percent efficiency decrease from 72 percent resulted in an increase in water cost per acre-foot of $0.125 per ¢/kWh while a 2 percent decrease in efficiency from 50 percent resulted in an in-

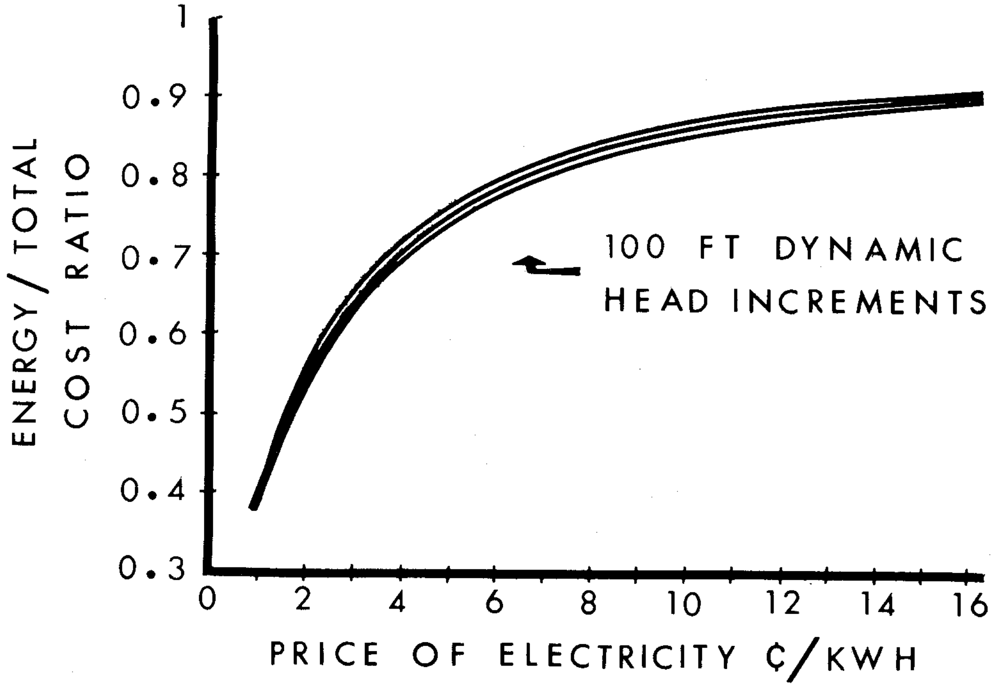

Figure 4. Ratio of energy to total cost as influenced by electricity price and average total dynamic head.

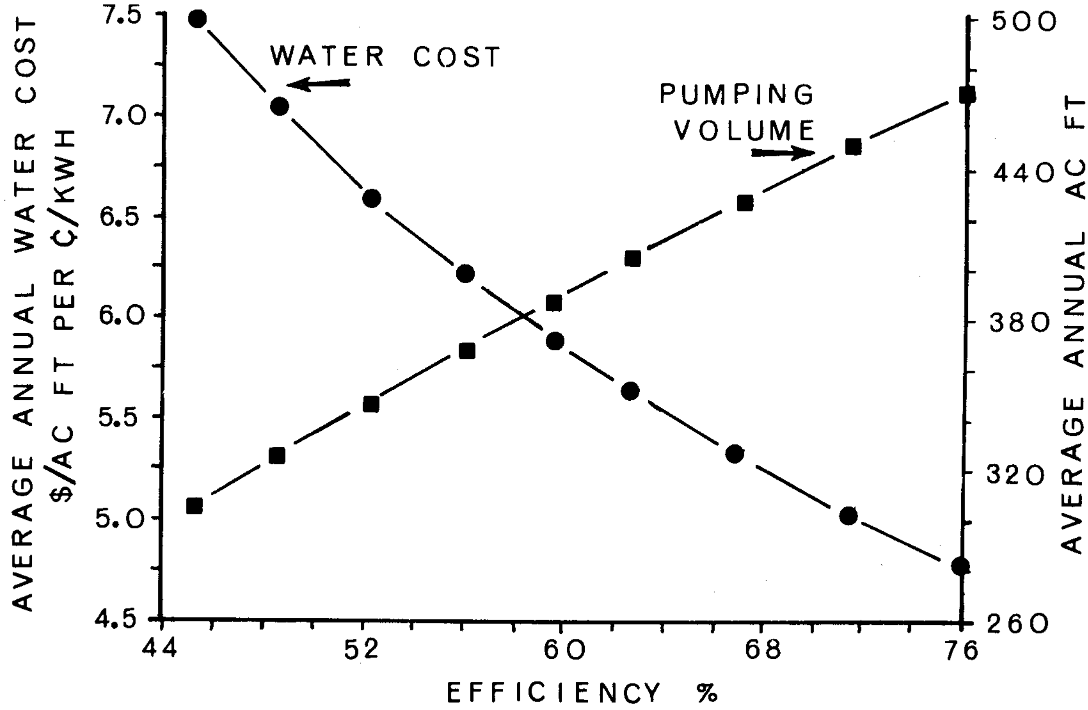

Figure 5. The effect of efficiency on pumping volume and water cost per cents per kilowatthour.