

Economics is the fundamental decision criterion in irrigation and drainage engineering. This chapter helps answer the following questions. Does the improvement in crop income and/or reduction in labor, energy, and water costs justify the capital expense of a new irrigation system? Which alternative irrigation system provides the highest profit and least environmental contamination? What is the optimal rate of water application? Engineering economic analysis uses the project life and expected rate of return to compare the expected present and future costs and benefits of proposed irrigation systems. If the system is profitable at the required rate of return, then the decision is made to invest in the system. Crop water production functions (CWPf) that have been developed in experiments show the relationship between seasonal depth of water applied and crop yield. Combined with water and energy cost information, they enable the calculation of the optimal depth of water application.

Crop Water Production Function

There is a direct relationship between total depth of irrigation water applied during the growing season and crop yield: if water uptake by the plant is limited, then transpiration and other plant processes such as photosynthesis may be limited. The relationships between yield and water application depth (CWPf) for individual crops have been developed in experiments with varying depths of applied water per season in different irrigation treatments. A cotton CWPf (dashed red line) is shown in Fig. 2.1.

In-class Exercise 2.1 Why does increasing the depth of irrigation water applied per season reach a point of diminishing returns?

Why is there a nearly linear relationship between evapotranspiration (ET) and yield and a nonlinear relationship between applied water and yield?

The yield vs. applied water curve (Cuenca 1989), in Fig. 2.1 was based on an experiment conducted by Grimes and El-Zik (1990). They derived the following equation:

$$Y_a = -3954 + 1067(AW_{CWPf})^{0.5} - 54.14(AW_{CWPf}) \quad (2.1)$$

where

AW_{CWPf} = depth of applied water used in calculation of yield, cm.

Y_a = actual yield per ha, kg/ha.

Irrigation (AW) is often supplemented by precipitation. Thus, precipitation should be added to Eq. 2.1.

$$Y_a = -3954 + 1067(AW_{CWPf} + P)^{0.5} - 54.14(AW_{CWPf} + P) \quad (2.2)$$

where

P = precipitation, cm.

Many irrigation systems waste water to surface runoff, nonuniformity, or leaching. If this is the case, then not all of the applied water is utilized for crop growth. The amount used divided by amount applied is the efficiency. The difference in efficiency between the experimental irrigation system used to develop the crop water production function and the field irrigation system should be accounted for. If the experimental (CWPf) irrigation system efficiency is 90 % (a reasonable assumption), then the relationship between gross depth of irrigation water (AW) applied and the depth referred to Eq. 2.1 (AW_{CWPf}) is calculated with the following equation:

$$AW = \frac{AW_{CWPf}}{(100 \% - (90 \% - Eff))/100} \quad (2.3)$$

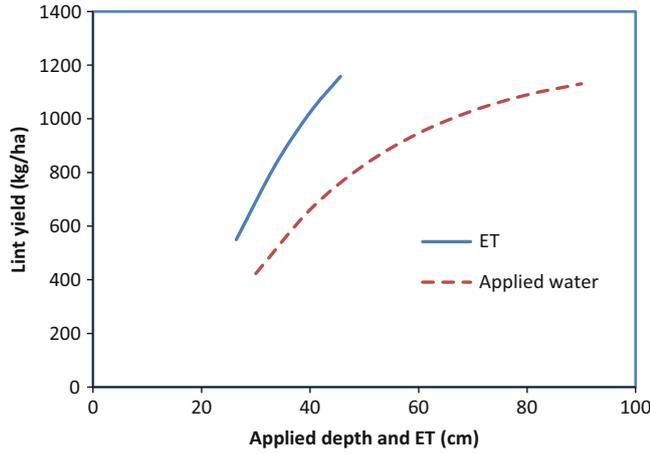


Fig. 2.1 Yield versus applied water (AW_{CWPF}) for cotton (After Grimes and El-Zik 1990)

where

Eff = efficiency of field irrigation system (excluding preirrigation), %

AW = Actual gross depth of applied water used to calculate water cost. .

Preirrigation may be needed to germinate the crop, and most of this water is often wasted as leachate or runoff. For example, germination of cotton in a field with a sloping furrow irrigation system often requires 2 ft depth (60 cm depth) of preirrigation water in order to wet the top of the planting bed. Most of this water is wasted as runoff. Preirrigation can be added to Eq. 2.3.

$$AW = \frac{AW_{CWPF}}{(100\% - (90\% - Eff))/100 + preirrigation} \quad (2.4)$$

Water cost is normally (but not always) calculated on a volume basis (m^3 , ac-ft, ha-cm). Because it takes $100 m^3$ to cover a 1 ha area to a depth of 1 cm, the cost in \$/ha-cm is equal to $100 * \$/m^3$. Thus, if the unit of AW is cm, then the cost of water in \$/ha is

$$WC = \$/m^3 * 100 * AW \quad (2.5)$$

where

WC = water cost, \$/ha.

If only water cost is considered, then profit is calculated as follows:

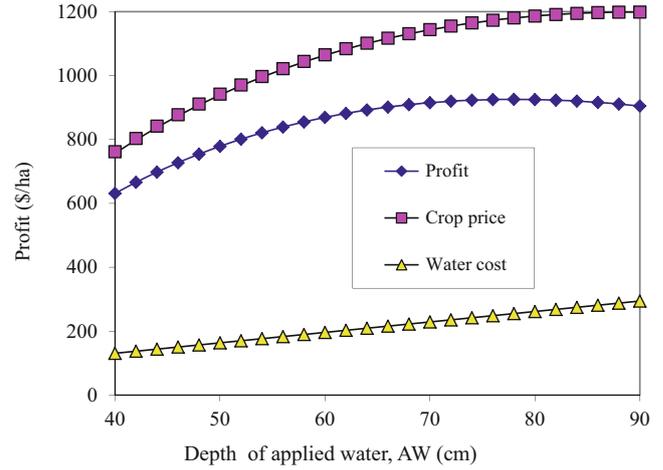


Fig. 2.2 Value of yield, water, and profit per ha for drip irrigated cotton (Example 2.1)

$$Pr = Y_a * (\$/Y_a) - WC \quad (2.6)$$

where

Pr = benefit or profit, \$/ha.

The maximum profit can be found by setting the derivative $d(Pr)/d(AW)$ equal to zero. Alternatively, a spreadsheet can be used to find the maximum profit.

Example 2.1 Find the depth of applied water (AW) that results in maximum profit with a drip irrigation system for the cotton CWPF by Grimes and El-Zik. Assume that 7.5 cm of precipitation infiltrates during the growing season. The cost of water is $\$0.0327/m^3$. The selling price of cotton is $\$0.92/kg$. Assume that preirrigation depth is 0 cm and $AW = AW_{CWPF}$. The drip irrigation system efficiency is 90 %.

$$Y_a = (-3954 + 1067(AW + 7.5cm))^{0.5} - 54.14(AW + 7.5cm)$$

$$Pr = \$0.92/kg * (-3954 + 1067(AW + 7.5cm))^{0.5} - 54.14(AW + 7.5cm) - \$3.27 * AW$$

The maximum profit (Fig. 2.2) is \$925/ha, which is found at an applied depth of water (AW_{CWPF}) equal to 79 cm (Fig. 2.2).

Example 2.2 Repeat Example 2.1, but use the surface irrigation with 60 cm preirrigation and 60 % efficiency.

$$WC = 3.27 * (AW_{CWPF} / (1 - (0.9 - 0.6)) + 60)$$

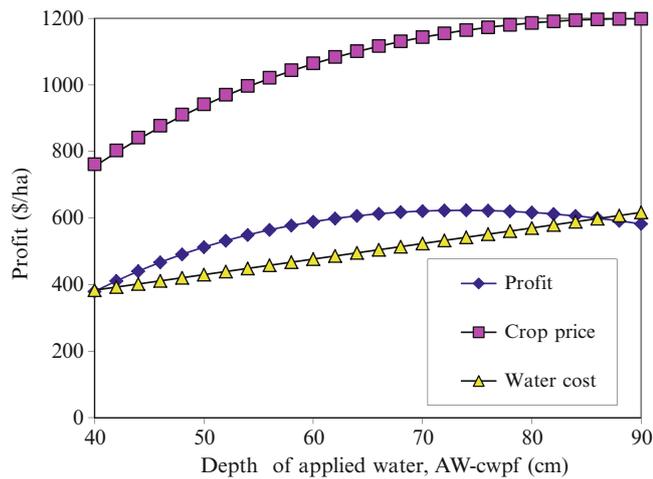


Fig. 2.3 Value of yield, water, and profit for surface irrigated cotton (Example 2.2)

$$Pr = \$0.92/\text{kg} * (-3954 + 1067(AW_{CWPF} + 7.5))^{0.5} - 54.14(AW_{CWPF} + 7.5) - WC$$

Maximum profit (\$623) is found at $AW_{CWPF} = 74$ cm (Fig. 2.3). The gross depth of water that is applied by the irrigation system is

$$\begin{aligned} \text{Depth applied} &= AW \\ &= AW_{CWPF} / (1 - (0.9 - 0.6)) + 60 \\ &= 74 / (1 - (0.9 - 0.6)) + 60 = 166 \text{ cm} \end{aligned}$$

The annual benefit is decreased by approximately \$300/ha from the drip irrigation system analyzed in Example 2.1. If the capital cost of a drip system is \$2,500 per ha, then the annualized cost of the system installation, assuming a 20 year project life and 8 % required rate, is approximately \$300/ha. Thus, all other things being equal, the cost of installing a drip system would be paid for by water savings. In addition, if there is a yield increase with drip irrigation, then the drip system would be a worthwhile investment.

Environmental Cost

Although often ignored, the environmental cost of an irrigation strategy should be considered during the design and optimization process. Erosion from sloping furrow irrigation systems is used here as an example. Eroded sediment causes sedimentation of channels, and it costs cities money to remove it from drinking water. In addition, the value of farmland is degraded if topsoil is eroded.

The Twin Falls tract in Idaho, with 85,000 ha, diverts water from the Snake River into its irrigation canal system. The practice of irrigation in the Twin Falls tract adds over

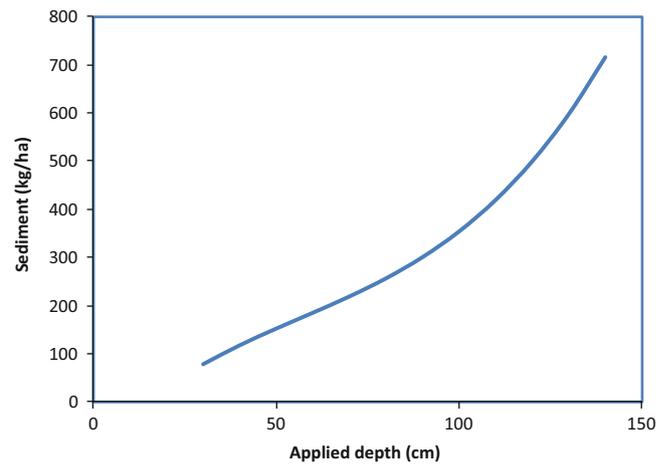


Fig. 2.4 Sediment yield versus applied water depth (cm)

40,000 metric tons of sediment to the Snake River (Brown et al., 1974) or approximately 500 kg/ha. Many of the farms in this area have lost nearly all topsoil from the upper end of fields. As more water is applied to a field, the amount of seasonal erosion increases. Thus, the relationship between sediment load and irrigation amount can be added into the economic analysis. Figure 2.4 shows a relationship between erosion and yearly applied depth of water to a surface irrigated field.

The line in Fig. 2.4 was generated with the following equation:

$$\text{Sediment}(\text{kg}/\text{ha}) = (4.62 * 10^{-5} i^3 - 7.84 * 10^{-3} i^2 + 0.77 i - 9.44) * 10^3 \quad (2.7)$$

where

i = seasonal gross depth of water applied by irrigation system, cm.

The environmental cost (EnvC) on a per hectare basis is

$$\text{EnvC}(\$/\text{ha}) = \$/\text{kg} * \text{kg}/\text{ha} \quad (2.8)$$

Equation 2.6 can be modified to include the environmental cost.

$$PR = Y_a * (\$/Y_a) - WC - \text{EnvC} \quad (2.9)$$

Example 2.3 Repeat Example 2.2, but include cost of erosion. The cost of erosion (land degradation and sediment removal from river water) is \$0.2/(kg/ha).

The actual depth of applied water is used to calculate the amount of erosion. For example, the irrigation depth at $AW_{CWPF} = 64$ cm is

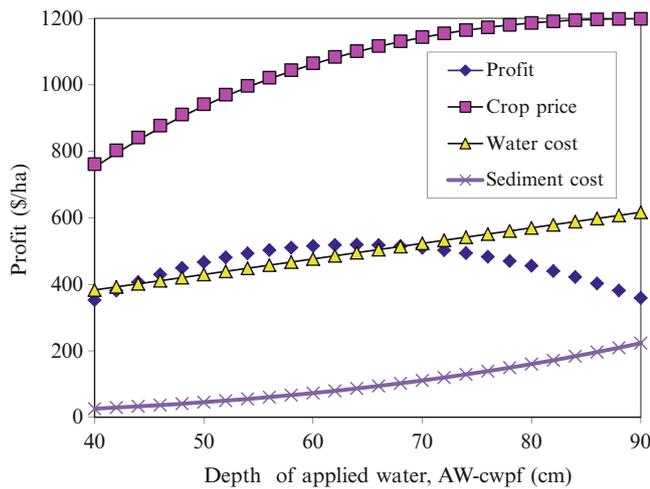


Fig. 2.5 Value of crop, water, profit, and erosion versus AW_{CWPF}

$$i = AW_{CWPF} / (1 - (0.9 - 0.6)) + 60 \\ = 64 / (1 - (0.9 - 0.6)) + 60 = 151 \text{ cm}$$

$$\text{Sediment} = (4.62 \cdot 10^{-5} \cdot (151)^3 - 0.00784 \cdot (151)^2 \\ + 0.477 \cdot (151) - 9.4449) \cdot 10 \\ = 429 \text{ kg/ha}$$

$$\text{EnvC} = 429 \text{ kg/ha} \cdot \$0.2/\text{kg} = \$86/\text{ha}$$

Using Eq. 2.9, maximum profit (\$519/ha) is found at $AW = 64$ cm with $i = 151$ cm. Figure 2.5 shows the results of the spreadsheet analysis, including environmental cost.

This example shows that the optimal economic depth of irrigation is generally reduced when environmental cost of irrigation is considered.

In-class Exercise 2.2 Should government charge farmers for sediments from surface irrigation systems that are discharged to streams?

Should farmers pay for the cost of dredging and for sediment removal from public drinking water supplies?

Should the government pay farmers to convert to pressurized irrigation if a farming region has erosive soils?

At the government policy level, should economic analysis of irrigation systems include all environmental degradation due to irrigation?

Transferring a CWPF from One Climatic Zone to Another

Linearized versions of crop water production functions are published by organizations such as the Food and Agriculture Organization (FAO) and used around the world. The cotton

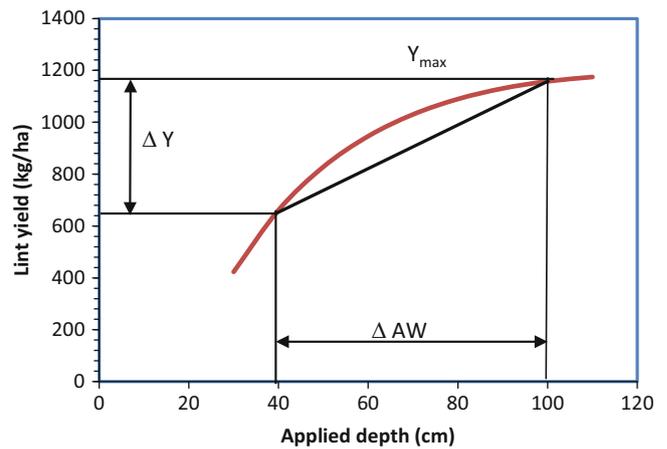


Fig. 2.6 Linearized crop water production curve

CWPF could be linearized (Fig. 2.6), but it obviously loses some accuracy in the process.

With a linear function, a relationship is developed between percent reduction in yield and percent reduction in required depth of water applied $\% \Delta Y / \% \Delta AW$. This approach makes the crop water production function more general and applicable to another region with a different water requirement and a different maximum yield.

$$Y_a = Y_{max} \left(1 - \frac{\% \Delta Y}{\% \Delta AW} \frac{AW_{req} - AW_{CWPF}}{AW_{req}} \right) \quad (2.10)$$

where

$\% \Delta AW$ = percent (fraction) change in applied water, dimensionless

$\% \Delta Y$ = percent (fraction) change in yield, dimensionless

Y_{max} = yield with no stress, kg/ha

AW_{req} = applied water depth with no yield reduction, cm.

Example 2.4 Calculate cotton yield. The required depth of applied water in a region is 100 cm, actual applied water depth is 80 cm, and the maximum yield is 1180 kg/ha.

From Fig. 2.6

$$\frac{\% \Delta Y}{\% \Delta AW} = \frac{(1161 - 641)/1161}{(100 - 40)/100} = 0.746$$

Equation 2.9

$$Y_a = Y_{max} \left(1 - \frac{\% \Delta Y}{\% \Delta AW} \frac{AW_{req} - AW_{CWPF}}{AW_{req}} \right) \\ = 1,180 \left(1 - 0.75 \frac{100 - 80}{100} \right) = 1,000 \text{ kg/ha}$$

The term $\% \Delta Y / \% \Delta AW$ is similar to K_y , the yield response factor used by the FAO. Based on Fig. 2.6 and previous discussions, it is easy to appreciate that an understanding of the experimental basis of K_y (and simplifications such as linearization) would help to avoid inaccuracies associated with misapplication of these coefficients. Equation 2.10 can be rearranged and set in the form used by the FAO.

$$1 - \left(\frac{Y_a}{Y_{\max}} \right) = K_y \left(1 - \frac{AW_{CWPF}}{AW_{req}} \right) \quad (2.11)$$

Combined Estimation of Crop Yield

Crop yield is a function of all stresses, included salinity, water, nitrogen, pest, and other stresses. Research has shown that the yield reduction due to combined stress factors (water, pests, and nutrients) can be calculated as the product of the fractions of yield due to the individual stress factors.

Example 2.5 There is 10 % yield loss due to pests, 10 % yield loss due to salinity and the depth of applied water to sugar beets is 80 % of that required. Maximum sugar beet yield is 40 t/ha. What is the yield?

Percent reduction due to water stress from example 2
 – 4 : $37/40 * 100 \% = 93 \%$

Expected yield = $40 \text{ t/ha} * (0.93 * 0.9 * 0.9) = 30 \text{ t/ha}$.

Irrigation Uniformity and Economics

Infiltration is generally higher at the furrow inlet than at the end of the furrow (Fig. 2.7): the furrow has an infiltrated depth that is 20 % greater at the beginning than the end; thus, if the end of the furrow is provided the optimal depth of water, then the upper end of the furrow receives excessive water.

Growers do not necessarily apply the target or optimal application depth to the minimum infiltration point at the end of the field. Instead, they often apply less than the target depth at the end of the field in order to avoid excessive overwatering of the upper end of the field. The *Variable water application* worksheet (Fig. 2.8) enables the calculation of yield at each furrow position as a function of the varying infiltration depths along the furrow. In the worksheet, the user inputs data in the white cells and the yellow cells are calculated.

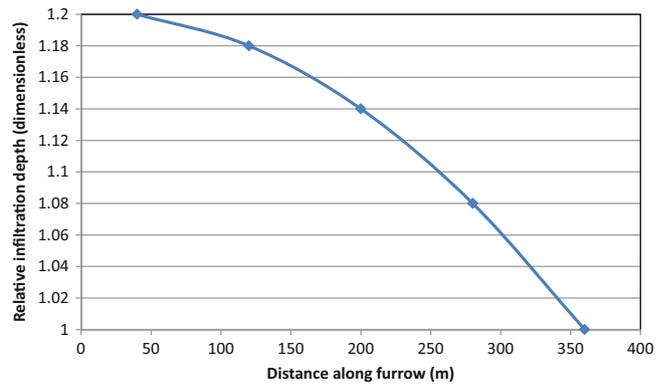


Fig. 2.7 Relative infiltration depths along 400 m length furrow divided into five sections

The target depth is in cell F1. The fraction of the target depth applied at the end of the field is specified in cell F2. The average AW_{CWPF} in column D is multiplied by $1 +$ runoff fraction (cell 34) in order to find the AW (gross depth of water) applied to the field. The runoff depth is also used to calculate the cost of erosion. The final profit (benefit – cost) in cell C5 is the average yield benefit minus the sum of water cost and sediment cost. The fraction of target depth at end of the furrow (cell F2) can be adjusted until the profit (cell C5) is maximized.

Engineering Economic Analysis

Engineering economic combines present (capital investment) and future (water cost, crop yield, energy cost, and labor) benefits and costs into one number. Conversion to a pressurized system may result in lower water costs and greater crop yield but have higher energy and capital costs; engineering economic analysis shows whether conversion to the pressurized system will ultimately result in greater profit for the farmer. It does this by converting all future costs and benefits to the present value based on the time value of money.

The required rate of return is the interest rate that a company expects to earn on investments. For example, if someone can invest retirement money in a retirement account at a guaranteed fixed return of 6 %, then it would be unwise for the person to invest retirement money elsewhere for an interest rate less than 6 %. In the jargon of engineering economic analysis, the person's required rate of return is 6 %. In engineering economic analysis, if a proposed project returns a profit at the required rate of return, even if the profit is only one dollar, then the decision is made to invest in the project.

	A	B	C	D	E	F	G	H	I	J	K
1	Target AW-cwvf depth from CWPF worksheet					66		Average AW-CWPF (cm)			67.27
2	Fraction of Target depth at end of furrow (specified)					0.91		Average leached depth (cm)			2.68
3	Runoff percentage (specified)					20%		Average useful depth (cm)			64.58
4								Total applied (AW - cm)			144.08
5	Benefits - costs		\$ 581.98					Efficiency (w/o preirrigation)			77%
6								Efficiency (including preirrigation)			45%
7	Hide chart		View chart					Cost of water (\$/ha)			\$ (471.15)
8								Cost of sediment (\$/ha)			\$ (69.48)
9								Average yield benefit (\$/ha)			\$1,122.62
10	Distance (m)	Fraction of end depth	Fraction of target depth	AW-cwvf	Excess Leached depth (cm)	Yield (\$/ha)					
11	40	1.2	1.092	72.072	6.072	1155.471					
12	120	1.18	1.0738	70.8708	4.8708	1148.957					
13	200	1.14	1.0374	68.4684	2.4684	1134.385					
14	280	1.08	0.9828	64.8648	0	1108.482					
15	360	1	0.91	60.06	0	1065.817					

Fig. 2.8 Variable water application worksheet

The future value of money is calculated with the following formula:

$$F = P(1 + i)^n \tag{2.12}$$

where

- F = future value
- P = present value
- i = interest rate
- n = number of years.

Example 2.6 If \$1.00 is placed into an account for 5 years at an interest rate of 6 %, then the value in 5 years is

$$F = (\$1.00) * (1 + 0.06)^5 = \$1.34$$

On the other hand, money that is received in 5 years is not worth as much as it is today and should be discounted. The present value of money received in the future is

$$P = \frac{F}{(1 + i)^n} \tag{2.13}$$

Example 2.7 The expected annual income from a project is \$500/yr for 5 years, and the project requires a \$2,000 investment. Determine whether or not to invest in the project at two required rates of return: 6 % and 8 %.

The net present value at a 6 % required rate of return:

$$P = \frac{500}{(1 + 0.06)^1} + \frac{500}{(1 + 0.06)^2} + \frac{500}{(1 + 0.06)^3} + \frac{500}{(1 + 0.06)^4} + \frac{500}{(1 + 0.06)^5} - 2,000$$

$$= 472 + 445 + 419 + 396 + 373 - 2,000 = \$106$$

Because the present value of the investment is greater than zero (\$106) at a 6 % required rate of return, the decision is made to invest in the project.

The net present value at an 8 % required rate of return:

$$P = \frac{500}{(1 + 0.08)^1} + \frac{500}{(1 + 0.08)^2} + \frac{500}{(1 + 0.08)^3} + \frac{500}{(1 + 0.08)^4} + \frac{500}{(1 + 0.08)^5} - 2,000$$

$$= 463 + 429 + 397 + 367 + 340 - 2,000 = -\$4$$

Because the present value of the investment is less than zero (-\$4) at the 8 % required rate of return, the decision would be not to invest in the project if the ROR was 8 %.

Engineering economic analysis can also account for rate of growth, inflation, depreciation, and other factors. Many of these functions are available in Excel: go to INSERT – FUNCTION – FINANCIAL to access financial functions. The PV calculator (present value from series of future payments) is shown in Fig. 2.9. This calculator will convert an annual series to payments to the present value. For example, the PV calculator in Fig. 2.9 calculates the present value of the 5 payments of \$500 at an 8 % interest rate as in Example 2.7. The length of the project in Example 2.7 is 5 years. Engineering economic analysis

always includes the lifespan of the project. A typical project lifespan is 20 years.

The following parameters are often incorporated into engineering economic analysis for irrigation systems:

- Component replacement (-)
- Crop yield or improvement in crop yield with the new irrigation system (+)
- Energy cost (-)
- Capital investment (-)
- Water cost (-)
- Labor cost (-)
- Environmental cost (-)
- Maintenance (-)
- Salvage value (+)

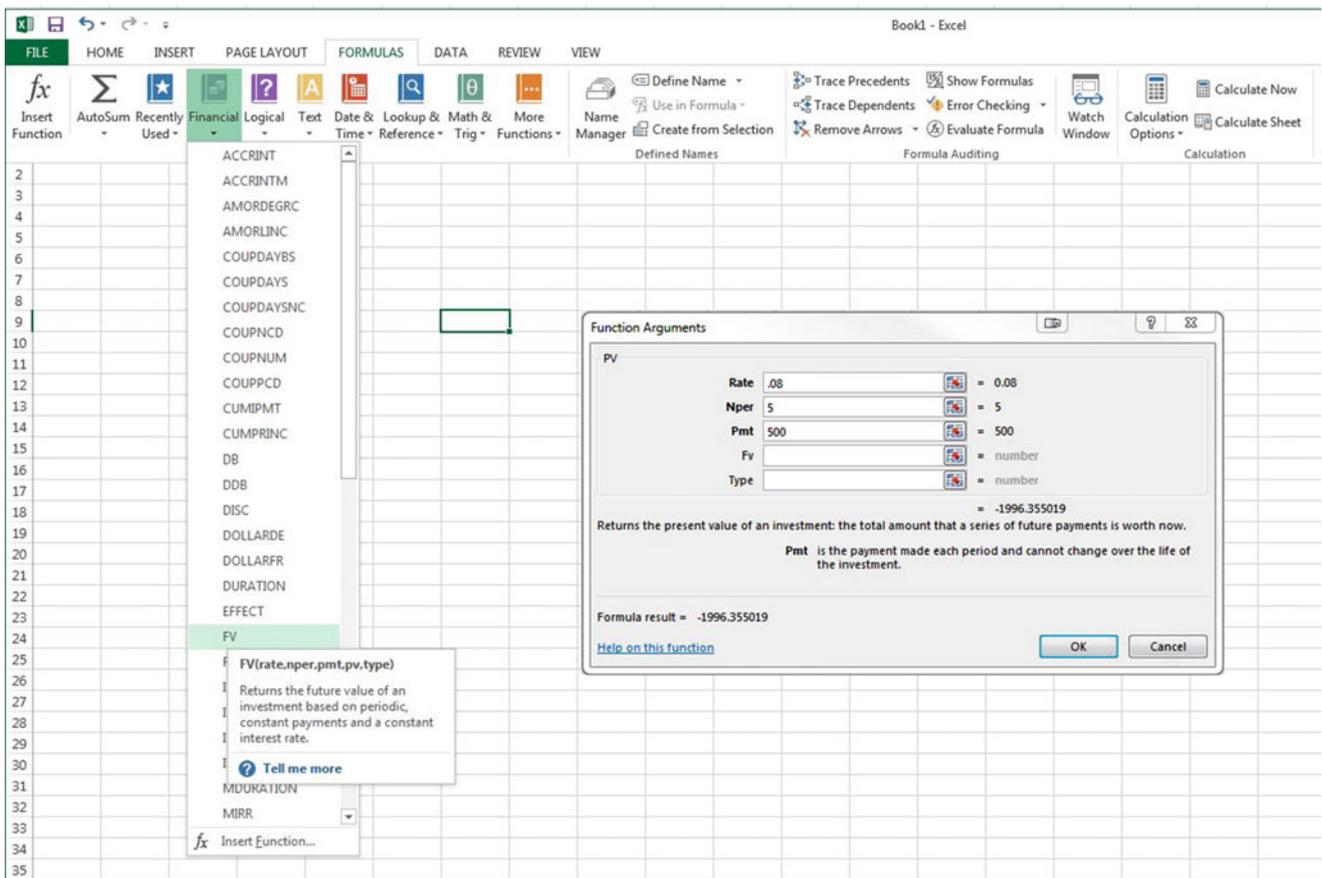


Fig. 2.9 Present value calculator (PV) in excel

Table 2.1 Typical life and annual maintenance cost percentage for irrigation system components (Credit: NRCS NEH, part 652, irrigation guide, Chap 5)

System and components	Life (yr)	Annual maint. (% of cost)	System and components	Life (yr)	Annual maint. (% of cost)
Sprinkler systems	10–15	2–6	Surface & subsurface systems	15	5
Hand move	15 +	2	Related components		
Side or wheel roll	15 +	2			
End tow	10 +	3		Pipelines	
Side move w/drag lines	15 +	4	Burled thermoplastic	25 +	1
Stationary gun type	15 +	2	Buried steel	25	1
Center pivot-standard	15 +	5	Surface aluminum	20 +	2
Linear move	15 +	6	Surface thermoplastic	5 +	4
Cable tow	10 +	6	Hurled nonreinforced concrete	25 +	1
Hose pull	15 +	6	Buried galv. steel	25 +	1
Traveling gun type	10 +	6	Buried corrugated metal	25 +	1
Fixed or solid set			Buried reinforced PMP	25 +	1
Permanent	20 +	1	Gated pipe, rigid, surface	10 +	2
Portable	15 +	2	Surge valves	10 +	6
Sprinkler gear driven, impact & spray heads	5–10	6	Pumps		
Valves	10–25	3	pump only	15 +	3
			w/electric motors	10 +	3
Micro systems ^{1/}	1–20	2–10	w/internal combustion engine	10 +	6
Drip	5–10	3			
Spray	5–10	3	Wells	25 +	1
Bubbler	15 +	2	Linings		
Send-rigid, hurled	10–20	2	Nonreinforced concrete	15 +	5
Semi-rigid, surface	10	2	Flexible membrane	10	5
Flexible, thin wall, buried	10	2	Reinforced concrete	20 +	1
Flexible, thin wall, surface	1–5	10			
Emitters & heads	5–10	6	Land grading, leveling ^{2/}		
Filters, injectors, valves	10 +	7	Reservoirs ^{3/}		

Expected annual maintenance costs and component replacement periods for different irrigation systems and components have been compiled by the NRCS in Table 2.1. Replacement costs can be incorporated into the economic analysis if the project lifespan is longer than the component life. The lifespan of PVC pipe is 25+ years. Thus, it would not be replaced in a 20 year economic analysis. However, the lifespan of thin wall subsurface drip irrigation tubing may be 2 years. Thus, the expense of replacing the tubing every 2 years would be incorporated in the spreadsheet and discounted back to the present value. Table 2.1 is a general guide. The lifespan of irrigation components is dependent on management, maintenance, soil quality, and water quality.

The value of the crop in future years is a function of many economic variables. Inflation of either crop prices or

expenses can have a dramatic effect on profit. If expenses increase and crop prices do not, then farming can become less profitable, as shown in Example 2.8.

Example 2.8 Determine the present value of the income from alfalfa 6 years from now at a required rate of return of 7 %. (1) Assume no inflation. (2) Assume inflation of costs of 5 % per year and no inflation in the selling price of alfalfa. The present value of alfalfa production is \$631/acre-yr. Operating expenses are \$321/acre-yr.

(1) No inflation.

$$\text{Present value of year 6 profit (without inflation)} \\ (\$631 - \$321) * \left(1 / (1 + 0.07)^6\right) = \$207.$$

(2) Costs inflate at a rate of 5 % per year.

Costs in year 6 :	$\$321(1.05)^6 = \$430/\text{acre.}$
Profit in year 6	$\$631 - \$430 = \$201/\text{acre.}$
Present value of year 6 profit(with inflation)	$\$201 * \left(1/(1 + 0.07)^6\right) = \$134/\text{acre.}$

Crops are generally rotated in order to prevent crop diseases and soil degradation. Previously unfarmed soils or soils that have undergone major land leveling often require development before they can support crops with higher cash value. If soil in newly developed farms have a high initial salt content, as is the case with desert lands, salts must be leached from the soil during the first year of production. Salt tolerant crops such as sorghum, wheat, or barley, can be grown in the first seasons. After 1 or 2 years of grain crops, many farmers plant alfalfa for 3 years. Finally, the field is ready for higher value crops such as vegetables. For tree crops, the economic analysis must include the fact that fruit production does not begin for several years. It should also include an increasing rate of water application as the trees mature. A crop rotation or crop development plan must be specified in order to estimate annual income from a proposed farm or irrigation system.

Energy cost (pumping cost) is a function of pressure requirement, volume of applied water, pump efficiency, friction loss in pipes and valves, and the cost of energy.

Energy (joules) can be calculated based on change in the potential energy of the water.

$$E = mgh/\text{Eff}_p = V\rho gh/\text{Eff}_p = iA\rho gh/\text{Eff}_p \quad (2.14)$$

where

E = energy, J

m = mass of water, kg

g = gravity, m/sec^2

h = pump pressure, m

Eff_p = efficiency of the pump, dimensionless

V = gross volume applied to the field

ρ = density, kg/m^3

i = depth applied, m

A = field area, m^2 .

Equation 2.14 can be rewritten in terms of irrigation parameters.

$$E(\text{Joules}/\text{ha}) = \frac{98,000 (i_{mm})(h)}{\text{Eff}_p} \quad (2.15)$$

where

i_{mm} = depth applied per year, mm.

Energy is generally sold in units of kW-hr.

$$E(\text{kW} - \text{hr}/\text{ha}) = \frac{0.0272 (i_{mm})(h)}{\text{Eff}} \quad (2.16)$$

Energy can be also be calculated as the product of pump power and time of pumping. Energy per ha = (pump power) (time)/(field area).

$$\text{Energy}(\text{kW} - \text{hr}/\text{ha}) = P t/A \quad (2.17)$$

where

A = Area, ha.

P = Pump power, kW

t = Seasonal pumping time, hr.

Example 2.9 Calculate the cost of energy to pump water for surface irrigation of cotton for 200 ha of land with an irrigation system that requires 3 m pressure head, and a pump that operates at 70 % efficiency. The cost of energy is \$0.10/kW-hr. Assume that the surface irrigation system water application efficiency is 65 %. Cotton requires 91 cm of water per year.

The irrigation system must apply 910 mm/0.65 = 1,400 mm

$$E = \frac{0.0272(1,400 \text{ mm})(3 \text{ m})}{0.70} = 163 \text{ kW} - \text{hr}/\text{ha}$$

$$(\$/\text{ha}) = \left(\frac{163 \text{ kW} - \text{hr}}{\text{ha}}\right) \left(\frac{\$0.10}{\text{kW} - \text{hr}}\right) = \$16.30/\text{ha}$$

Total annual cost for 200 ha = $\$16.30/\text{ha} * 200 \text{ ha} = \$3,260$

When determining whether an existing surface irrigation system should be replaced with a new pressurized irrigation

system, the economic benefit of the new irrigation system can be estimated based on the change in costs and benefits rather than the total costs and benefits. This concept is demonstrated in the following example.

Example 2.10 A farmer is considering converting his sloping furrow surface irrigation system to a new center pivot irrigation system for alfalfa. The installation cost for the new system is \$2,000/ha. Should the farmer install center pivots?

Given

Energy

The center pivot irrigation system will require 20 m pressure head. Alfalfa requires 150 cm/yr with the center pivot system. The cost of energy is \$0.10/kW-hr. Pumping efficiency is 80 %. No pumping is required for the surface irrigation system.

Water

Annual cost drops from \$250/ha with the surface system to \$200/ha with the pivot system.

Labor

One irrigator who makes \$25,000 per year is usually required for every 100 acres (40 ha) of sloping furrow surface irrigation. This works out to approximately \$625/ha. Assume that yearly labor cost for a pivot irrigation system is \$200/ha (this estimate is probably high).

Environmental

Environmental cost drops from \$100/ha for surface irrigation due to surface runoff of sediment to \$0/ha with pressurized irrigation.

Economics

The required rate of return is 8 %. The length of the project is 20 years.

Maintenance

Maintenance cost of the pivot and surface irrigation systems is the same.

Yield

The yield value increases from \$630/ha to \$760/ha with the pressurized irrigation system.

Solution

Add all the annual costs and benefits. Convert this number back to a present value and compare to the capital cost.

Calculate energy costs with the new center pivot system.

$$E = \frac{0.0272(1,500 \text{ mm})(20 \text{ m})}{0.80} = 1,020 \text{ kW} - \text{hr}/\text{ha}$$

$$(\$/\text{ha}) = \left(\frac{1,020 \text{ kW} - \text{hr}}{\text{ha}} \right) \left(\frac{\$0.10}{\text{kW} - \text{hr}} \right) = \$102/\text{ha}$$

Annual costs and benefits

Input a decrease in costs or increase in benefits as a+.

Input an increase in costs or a decrease in benefits as a-

	Current surface system	Pivot system	Change
Yield Income	\$630/ha	\$750/ha	+\$120/ha
Labor costs	\$625/ha	\$200/ha	+\$425/ha
Water cost	\$250/ha	\$200/ha	+\$50/ha
Environment	\$100/ha	\$0/ha	+\$100/ha
Energy	\$0/ha	\$102/ha	-\$102/ha
Change			+\$593/ha

Annual Benefits – Costs = +\$593/ha

Convert annual benefits to present value (20 years at 8 %) = \$5,822/ha

The benefits of the irrigation system – cost = \$5,822 – \$2,000 = \$3,822/ha

The decision is made to convert to center pivots because the present value is greater than zero.

Example 2.11 A farmer in a developing nation is considering converting his sloping furrow surface irrigation system to a new center pivot irrigation system for alfalfa. The installation cost for the new system is \$2,000/ha. Should the farmer install center pivots?

Given

All parameters are the same as Example 2.10 except labor.

Labor

One irrigator who makes \$2,000 per year is required for every 40 ha of sloping furrow surface irrigation. Yearly labor costs for a pivot irrigation system are \$35/ha.

Solution

Annual costs and benefits

Input a decrease in costs or increase in benefits as a+.

Input an increase in costs or a decrease in benefits as a-

	Current surface system	Pivot system	Change
Yield income	\$630/ha	\$750/ha	+\$120/ha
Labor costs	\$50/ha	\$35/ha	+\$15/ha
Water cost	\$250/ha	\$200/ha	+\$50/ha
Environment	\$100/ha	\$0/ha	+\$40/ha
Energy	\$0/ha	\$102/ha	-\$102/ha
Change			+\$123/ha

Annual Benefits – Costs = +\$123/ha

Convert Annual Benefits to present value (20 years at 8 %) = \$1,207/ha

The benefits of the irrigation system – cost = \$1,207–\$2,000 = –\$793/ha

The farmer should not convert to center pivots because the net present value is less than zero. In a country with lower labor costs, the decision is reversed from the previous example.

Cash Flow Diagrams

Cash flow diagrams show the expected crop income, energy costs, water costs, replacement costs, etc. . . each year for the life of the project. Inflation and other changes in prices are incorporated into the spreadsheet. It is especially important in agriculture with the development of new lands or planting of trees to accurately calculate the expected yield and costs each year.

A consideration in many economic analyses is risk; however, the analyses in this section only use the expected average yield.

Total benefits minus costs are calculated each year for the cash flow diagram. The total for each year is then discounted to the present value based on the required rate of return. This process is demonstrated in the following example.

Example 2.12 Redo Example 2.10, but use the crop rotation for development of a new farm that is shown in Table 2.2. Also include the following inflation rates and price changes.

Given

It is expected that the selling price of alfalfa will inflate by 7 % each year and that the selling price of cotton, wheat, and sorghum will inflate by 5 % each year. The present annual benefit of growing alfalfa, wheat/sorghum, and wheat/cotton, neglecting water, labor, and energy costs, is \$1,000/ha, \$500/ha, \$700/ha, respectively.

The present annual cost of energy is \$100/ha; and the cost of energy is expected to inflate by 8 % per year for all crop rotations. The present annual cost of water is \$200/ha; and the cost of water is expected to inflate by 4 % per year for all crop rotations. The present annual cost of irrigation labor and maintenance is \$200/ha, and is expected to inflate by 5 % per year for all crop rotations.

There is no environmental cost.

The capital cost of purchasing the land (\$500/ha) and developing the farm (\$2,500 / ha) is \$3,000/ha. In addition,

Table 2.2 Crop rotation

Year	Winter	Summer	Year	Winter	Summer
1	Wheat	Sorghum	11	Wheat	Cotton
2	Alfalfa	Alfalfa	12	Wheat	Cotton
3	Alfalfa	Alfalfa	13	Wheat	Cotton
4	Alfalfa	Alfalfa	14	Alfalfa	Alfalfa
5	Wheat	Cotton	15	Alfalfa	Alfalfa
6	Wheat	Cotton	16	Alfalfa	Alfalfa
7	Wheat	Cotton	17	Wheat	Cotton
8	Alfalfa	Alfalfa	18	Wheat	Cotton
9	Alfalfa	Alfalfa	19	Wheat	Cotton
10	Alfalfa	Alfalfa	20	Alfalfa	Alfalfa

\$300 must be added for repairs and maintenance each year.

The crop rotation and expected annual benefit at current prices are shown in Table 2.2.

Solution

A cash flow diagram for the 20 year project is constructed in the *Cash flow* worksheet (Figs. 2.10 and 2.11). The future prices of the crops are based on their own inflation rates in cells C2:C8. The profit each year is summed and converted to the present value at the required rate of return.

The sum of present value annual costs and benefits at an 8 % required rate of return is \$326/ha. Thus, the project has a profit greater than the required rate of return and is recommended.

Customer Relations and Sales

From the point of view of many irrigation companies, the most important economic concern is selling irrigation systems or selling the design service for irrigation systems. In order to do this, one must gain the confidence of the farmer. One of the first things a farmer wants to know when considering a new system is the water and power requirement. The best way to lose the job is to stand there with your mouth open and not have an answer to these questions. A few simple equations for estimating water and power requirements should be memorized.

Irrigation system water requirements are based on the worst case – the part of the year when the plants require the most water. The rationale is that if the irrigation system supplies enough water during the time of the year with maximum evapotranspiration, then it will provide enough water during the rest of the year. It is up to the farmer to schedule the irrigation frequency during the rest of the year

Present Costs (\$/ha)		Inflation rate / yr	Net present value \$/ha		Annual costs and benefits (\$/ha)							
Water cost (\$/ha)	-200	0.04	Net present value \$/ha	\$ 326.04	Capital or salvage cost	Crop value	Water cost	Energy cost	Labor cost	Sum of annual	Present value	
Energy cost (\$/ha)	-100	0.08										
Labor cost (\$/ha)	-200	0.05										
Required rate of return		0.08										
Wheat/sorghum	400	0.05	Year	Winter	Summer	Present benefit	Inflation rate					
Alfalfa	1000	0.07										
Wheat/cotton	700	0.05										
0	-	-	-	-	-3000	0	0	0	0	\$(3,000.00)	\$(3,000.00)	
1	Wheat	Sorghum	400	0.05	-300	420	-208	-108	-210	\$(406.00)	\$(375.93)	
2	Alfalfa	Alfalfa	1000	0.07	-300	1145	-216	-117	-221	\$291.44	\$249.86	
3	Alfalfa	Alfalfa	1000	0.07	-300	1225	-225	-126	-232	\$342.57	\$271.95	
4	Alfalfa	Alfalfa	1000	0.07	-300	1311	-234	-136	-243	\$397.67	\$292.30	
5	Wheat	Cotton	700	0.05	-300	893	-243	-147	-255	\$(52.12)	\$(35.47)	
6	Wheat	Cotton	700	0.05	-300	938	-253	-159	-268	\$(41.70)	\$(26.28)	
7	Wheat	Cotton	700	0.05	-300	985	-263	-171	-281	\$(31.02)	\$(18.10)	
8	Alfalfa	Alfalfa	1000	0.07	-300	1718	-274	-185	-295	\$663.89	\$358.68	
9	Alfalfa	Alfalfa	1000	0.07	-300	1838	-285	-200	-310	\$743.63	\$372.00	
10	Alfalfa	Alfalfa	1000	0.07	-300	1967	-296	-216	-326	\$829.43	\$384.19	
11	Wheat	Cotton	700	0.05	-300	1197	-308	-233	-342	\$14.11	\$6.05	
12	Wheat	Cotton	700	0.05	-300	1257	-320	-252	-359	\$25.90	\$10.29	
13	Wheat	Cotton	700	0.05	-300	1320	-333	-272	-377	\$37.85	\$13.92	
14	Alfalfa	Alfalfa	1000	0.07	-300	2579	-346	-294	-396	\$1,242.49	\$423.02	
15	Alfalfa	Alfalfa	1000	0.07	-300	2759	-360	-317	-416	\$1,365.84	\$430.57	
16	Alfalfa	Alfalfa	1000	0.07	-300	2952	-375	-343	-437	\$1,498.40	\$437.37	
17	Wheat	Cotton	700	0.05	-300	1604	-390	-370	-458	\$86.43	\$23.36	
18	Wheat	Cotton	700	0.05	-300	1685	-405	-400	-481	\$98.54	\$24.66	
19	Wheat	Cotton	700	0.05	-300	1769	-421	-432	-505	\$110.54	\$25.61	
20	Alfalfa	Alfalfa	1000	0.07	-300	3870	-438	-466	-531	\$2,134.70	\$458.00	
										\$326.04		

Fig. 2.10 Annual crop value, water, energy, and labor from Cash flow worksheet

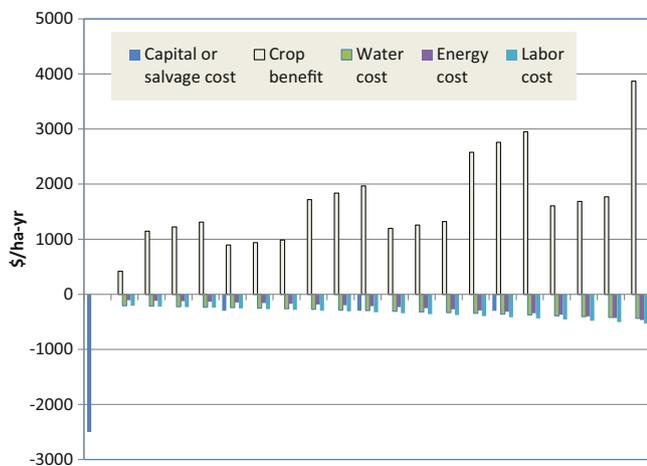


Fig. 2.11 Cash flow diagram

such that the water application matches the rate of evapotranspiration.

The irrigation system must supply a flow rate that is equal to the product of maximum crop evapotranspiration

(ET_{c-max} mm/day) and farm area (A) divided by the efficiency of the system.

$$Q = ET_{c-max} * A / \text{Eff} \quad (2.18)$$

Rules of thumb for estimating flow rate requirements can be developed in each region. For example, if the maximum expected evapotranspiration rate is 13 mm/day in a region, then the water requirement per acre or per hectare is calculated as follows:

$$ET_{c-max} = \frac{13 \text{ mm}}{\text{day}} \left(\frac{10,000 \text{ m}^2}{\text{ha}} \right) \left(\frac{1 \text{ m}}{1,000 \text{ mm}} \right) = \frac{130 \text{ m}^3}{\text{day ha}}$$

$$ET_{c-max} = \frac{130 \text{ m}^3}{\text{day}} \left(\frac{1 \text{ day}}{24 \text{ hr}} \right) \left(\frac{1 \text{ hr}}{60 \text{ min}} \right) \left(\frac{1,000 \text{ L}}{1 \text{ m}^3} \right) = \frac{90 \text{ L/min}}{\text{ha}}$$

$$ET_{c-max} = \frac{90 \text{ L/min}}{\text{ha}} \left(\frac{1 \text{ gal}}{3.785 \text{ L}} \right) \left(\frac{0.4047 \text{ ha}}{1 \text{ acre}} \right) = \frac{9.65 \text{ gpm}}{\text{ac}}$$

In-class Exercise 2.3 Develop a rule of thumb for pump flow rate requirement for a region that has a max ET = 10 mm/d. Assume system water application efficiency is 80 % and 10 % down time?

What pump flow capacity will be required for a 10 ha farm if $ET = 10$ mm/day?

The other number that a farmer wants to know is the required pump horsepower. The power is a function of flow rate, pressure, and efficiency.

$$P = Q\rho gh/\text{Eff} \quad (2.19)$$

where

P = power, W

Q = flow rate, m^3/sec

ρ = density of water, $1,000 \text{ kg}/\text{m}^3$

g = gravity, $9.8 \text{ m}/\text{sec}^2$

h = pressure head, m

Eff = efficiency, fraction.

Equation 2.20 can be simplified for metric and United States units. The Power is calculated for typical irrigation units as follows:

Metric:

$$\begin{aligned} \text{Power(kW)} &= (Q(\text{m}^3/\text{sec}) * H) / (0.102 * \text{Eff}) \\ \text{Power(mhp)} &= (Q(\text{L}/\text{min}) * H) / (4634 * \text{Eff}) \end{aligned} \quad (2.20)$$

where

Q = flow rate, m^3/sec (upper) or L/min (lower)

H = discharge pressure, m

Eff = pump energy efficiency, fraction

mhp = metric horsepower.

U.S.

$$HP = \frac{gpm * ft}{3,960 * \text{Eff}} \quad (2.21)$$

where

HP = horsepower, U.S. units

ft = ft of head

gpm = flow rate in gpm

Eff = efficiency of the pump, fraction.

Energy is generally sold in metric units: kW-hr. To convert from HP to kW, multiply by 0.746: $\text{kW} = \text{HP} * 0.746$. Metric horsepower (mhp) is almost the same as U.S. HP. $\text{HP} = \text{mhp} * 1.014$.

In-class Exercise 2.4 Students act out the following play about a typical meeting between the irrigation engineer and the client (this may be the only irrigation engineering play in history).

Josephine, the irrigation sales engineer from Irrigation Systems Design Company, drives up to McGillicutty Wellington Growing and Harvesting Farms (MWGH farms or My Way or Get Back to the Highway Farms) in her Chevrolet S10 pickup truck.

Mr. McGillicutty: "So Josephine, come on in and have a cup of coffee."

Josephine: "Don't mind if I do, Mr. McGillicutty."

Mr. McGillicutty: "Josephine, what size pump do I need if I want to convert my section of land (640 acres) to drip?"

Josephine makes the following silent mental calculation while she sips a cup of coffee.

$$640 * 10 = 6,400 \text{ gpm.}$$

Josephine: I can see that you are growing cotton and alfalfa, so Mr. McGillicutty, you would need somewhere between 6,000 and 7,000 gpm.

Mr. McGillicutty: "How much is that in cubic feet per second?"

Josephine: "Mr. McGillicutty, 450 gpm equals about 1 cfs, so that would be approximately 8 cfs."

Mr. McGillicutty: "No problem, we use quite a bit more than that for our current flood system. I am worried about bringing electrical power out for the pump. What horsepower pump would that require?"

Josephine: "If you want to irrigate 640 acres with drip irrigation, then you would probably need to generate about 30 psi pressure. Large pumps probably have an 80 % electrical efficiency." She then puts her coffee down, pulls out her calculator, and makes the following calculation:

$$30 \text{ PSI} * 2.31 = 70 \text{ ft}$$

$$\left(\frac{6,400 \text{ gpm} * 70 \text{ ft}}{3,960 * 0.8} \right) = 150 \text{ HP}$$

Josephine puts her cup of coffee down and says; "Mr. McGillicutty, you need 150 HP."

Mr. McGillicutty: "What is that in kilowatts?"

Josephine: "That would be about 110 kW."

Mr. McGillicutty: "That sounds reasonable. How soon can you design the system?"

Josephine: "I will get back to you in a few weeks."

During the process of design, it is quite typical for growers to make changes. In fact, many growers will make three or more major changes during the design process. This causes extra work.

There are many other practices that should be followed by the engineer in order to maintain good relationships with customers. Many of these are detailed in the *Turf and Landscape Best Management Practices* by the [Irrigation Association](#).

Questions

1. Why does increasing the depth of irrigation water applied per season reach a point of diminishing returns?
2. Why is there a nearly linear relationship between evapotranspiration (ET) and yield and a nonlinear relationship between applied water and yield?
3. How are the crop water production function and engineering economic analysis used to assess or manage irrigation systems.
4. Find the profit with the following parameters for the Grimes and El-Zik CWPF for drip irrigated cotton: 15 cm depth of precipitation, cost of water is $\$0.02/\text{m}^3$. The selling price of cotton is $\$0.90/\text{kg}$. Depth of applied water, $AW_{\text{CWPF}} = 62$ cm. Show your work.
5. For the parameters in question 4, calculate the optimal depth of water application, AW_{CWPF} . Do this problem in Excel and turn in the graph that shows the yield, cost of water, and profit vs. AW_{CWPF} .
6. For the parameters in question 4, calculate the profit for a surface irrigation system with 70 % efficiency at $AW_{\text{CWPF}} = 70$ cm. Preirrigation is 45 cm. The water from preirrigation provides no benefit for crop growth in this case. Do not consider erosion. Show your work.
7. For the parameters in question 6, find the optimal depth of water application, AW_{CWPF} . Do this problem in Excel, and turn in the graph that shows the yield, cost of water, and profit vs. AW_{CWPF} .
8. For the parameters in question 6, calculate the profit per ha, but include erosion with erosion calculated by Eq. 2.7 and the cost of erosion equal to $\$0.004/\text{kg}$.
9. For the parameters in question 8, find the optimal depth of water application, AW_{CWPF} . Do this problem in Excel, and turn in the graph that shows the yield, cost of water, cost of erosion, and profit vs. AW_{CWPF} .
10. Use the *Variable water application* worksheet. Keep all other parameters the same, but double the cost of water. Find the optimal depth of water application.
11. Use the *Variable water application* worksheet but change the number of furrow sections to 6 with the following multipliers of end furrow application. 1.5, 1.45, 1.33, 1.25, 1.13, and 1. Keep all other parameters the same as the original version. Find the optimal depth of water application.
12. Should government charge farmers with surface irrigation systems that discharge sediment to streams for the cost of dredging and for sediment removal from public drinking water supplies? Why or why not?
13. Should the government pay farmers to convert to pressurized irrigation if a farming region has erosive soils?
14. At the government policy level, should economic analysis of irrigation systems include all environmental degradation due to irrigation?
15. Calculate cotton yield if the required depth of applied water in a region is 120 cm, actual applied water depth is 80 cm, and the maximum yield is 1200 t/ha. Look at Fig. 2.6. Is your answer realistic?
16. There is 10 % yield loss due to pest stress in addition to the loss due to water stress calculated in question 15. What is the expected yield?
17. The expected annual income from a project is $\$600/\text{yr}$ for 5 years, and the project requires a $\$2,000$ investment. Determine whether or not to invest in the project at a 9 % required rate of return.
18. Determine the present value of the income from cotton 4 years from now for full water application and a required rate of return of 7 %. (1) Assume no inflation. (2) Assume inflation of 5 % per year in costs and no inflation in the selling price of cotton. Current yearly income is $\$854.25$, and current yearly expenses are $\$721.16$
19. Calculate the cost of energy to pump water for sprinkler irrigation alfalfa for 100 ha of land with an irrigation system that requires a 30 m pressure head, and a pump that operates at 80 % efficiency. The cost of energy is $\$0.10/\text{kW-hr}$. Assume that the sprinkler irrigation system water application efficiency is 75 %. Assume that alfalfa requires 5 m of water per year
20. Develop a rule of thumb for pump flow rate requirement for an area that has a max ET = 10 mm/d in terms of gpm/acre? The expected irrigation efficiency is 70 %, and the expected downtime is 10 %. What pump flow capacity will be required for a 10 acre farm? If the farm is divided into five irrigation zones, then what pump size is required?
21. For the flow rate in question 20, what motor horsepower is required and wattage is required if the pump operates at 100 ft pressure and is 85 % efficient?
22. Using the *Cash flow diagram* worksheet, redo the analysis for alfalfa planted every year.

References

- Brown M, Carter D, Bondurant J (1974) Sediment in irrigation and drainage waters and sediment inputs and outputs for two large tracts in Southern Idaho. *J Environ Qual* 3(4):347–351
- Cuenca RH (1989) *Irrigation system design*. Prentice Hall, Englewood Cliffs
- Grimes DW, El-Zik KM (1990) Cotton. In: Stewart BA, Nielsen DR (eds) *Irrigation of agricultural crops*. American Society of Agronomy, Madison, pp 741–773, Monograph # 30
- Irrigation Association. Turf and landscape best management practices. <http://www.irrigation.org/landscapebmps/>