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# ESTIMATION OF PEAK IRRIGATION REQUIREMENTS FOR DESIGN PURPOSES AFFECTED BY THE TYPE OF IRRIGATION SYSTEM

(LA ESTIMACIÓN DE LOS REQUERIMIENTOS PICO DE RIEGO CON FINES DE DISEÑO AFECTADO POR EL TIPO DE SISTEMA DE RIEGO)

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## Abstract

A key variable in an irrigation system design is estimation of the amount of water to be applied through the crop cycle. Specifically, what is the peak demand required to design a water network for critical conditions. Insufficient knowledge of crop water needs can produce an over-design of the network with unnecessary costs or under-design of the network resulting in the inability to satisfy maximum crop water demands. Different irrigation systems must supply water in quantities and at times needed to meet irrigation requirements and schedules. The study's objective was to analyze the effect of the irrigation system on the estimation of the maximum irrigation requirements as well as the impact of the precipitation for design purposes. The Design Daily Irrigation Requirements (DDIR) were determined from several years of daily irrigation requirement (DIR) data. DIR's for each year of climatic record were computed with the software CROPWAT 8.0. A frequency analysis of thirty years of DDIR values was made to account for year-to-year fluctuations in climate. Such analysis allows a probability of occurrence to be assigned to each DDIR. The results showed that the frequency analysis allows identification of a DDIR that will, on average, be exceeded 50, 20, 10, and 5 percent of the time (return periods of 2, 5, 10 and 20 years respectively) to be determined. For example, a 5-year return period indicates that historically, the DDIR has been exceeded once in 5 years.

**Keywords:** Design Daily Irrigation Requirement (DDIR), irrigation scheduling, frequency analysis, CROPWAT 8.0.

## Introduction

Irrigation systems must supply water at rates, in quantities, and at times needed to meet irrigation requirements and schedules. They bring water from the water source, convey it to the crops, distribute it over the farm or area being irrigated, and provide a mean for measuring and regulating flow. The job of the irrigation engineer is to match the system to the physical and economic situation in which the irrigation system is to operate. The primary steps in farm irrigation system design begin with collecting data needed for design, then identifying and evaluating a water source. After we need to determine the Design Daily Irrigation Requirement (DDIR), then designing an alternative system for the farm, followed by this, assessing the performance of alternative system designs, then determining the annual cost of alternative system designs and finally selecting the most suitable irrigation system design. In this study, we are primarily focused on the determination of the design daily irrigation requirement. DDIR is typically the rate at which an irrigation system must supply water to achieve the desired level of irrigation. In some conditions, however, the most significant daily irrigation requirement is associated with land preparation (for instance, rice paddy formation) and not evapotranspiration ET (James, L. 1993).

In this paper, it is assumed that ET determines DDIR. DDIR has dimensions of length per unit of time. Conventional units for DDIR are millimeters per day (mm/day) or liters per minute per hectare (l/min/ha). The DDIR for an irrigation system varies depending the type of crop, soils, and climate. DDIR values are largest for crops that have relatively shallow rooting depths, or for crops that are sensitive to water stress, and use water rapidly. Crops located in climates with high daily ET rates and low precipitation have the largest DDIR as well (James, L. 1993). Typically, DDIR's for crops grown in soils with low water holding capacities, such as sands, are higher than for those crops grown in finer textured soils with higher water holding capacities such as clays. This is due to the fact that interval between irrigations (irrigation interval) increases with water holding capacity and the average daily irrigation requirement is smallest for longer irrigation intervals (James, L. 1993).

## Materials and Methods

### Study area

The study was carried out in Texcoco municipality located in the State of Mexico, 25 km northeast of Mexico City (Fig. 1). The climate is temperate and semi-arid with a median temperature of 15.9 °C, and limited frosts. Most rains come during June and October.


**Figure 1.** Texcoco location in Mexico.

Most Texcoco soils used for agriculture are loamy. Their surface layers are brown and have medium texture. The remaining layers are black, saturated soils. They originate from recent alluvial and lacustrine deposits of mixed materials. Variation in these soil layers ranges from loam to sandy loam, presenting as dark brown to grayish brown, respectively. Their electrical conductivity varies from 4 to 8 mmhos/cm in the first 60 to 80 cm, and from 10 to 16 mmhos/ cm in the deep layers. (Cachón Ayora et al., 1974).

**Determination of the Evapotranspiration using CROPWAT**

The daily climatic data was obtained from the Chapingo Weather Station (19°30’00’’N, 98°51’00’’W) and then, it was used as input in the CROPWAT 8.0 model. A simulation period of 30 years (from 1985 to 2014) with four common well-produced crops in Texcoco was carried out. These crops are maize, bean, oat, and tomato. See Tables 1a and 1b for crop data information. CROPWAT 8.0 for Windows is a computer program developed by the Land and Water Development Division of FAO. It is used for the calculation of crop water requirements and irrigation requirements based on soil, climate and crop data (FAO, 1992). The development of irrigation schedules and evaluation of rainfed and irrigation practices are based on a daily soil-moisture balance using various options for water supply and irrigation management conditions.

**Table 1a.** Crop cycle, planting, and harvesting dates commonly presented at Texcoco, Mexico.

| Crop | Planting date | Harvest | Crop cycle Total (days) |
|---|---|---|---|
| **Maize** | April-01 | July-09 | 100 |
| **Bean** | May-01 | Aug-18 | 110 |
| **Oat** | Sep-01 | Dec-19 | 110 |
| **Tomato** | March-01 | May-14 | 75 |

**Table 1b.** Continuation of the crops data.

| Crop | Rooting depth (m) | Crop height (m) | Critical depletion (fraction) |
|---|---|---|---|
| **Maize** | 1.0 | 2.0 | 0.55 |
| **Bean** | 0.9 | 0.6 | 0.45 |
| **Oat** | 1.5 | 1.0 | 0.55 |
| **Tomato** | 1.0 | 0.5 | 0.40 |

CROPWAT 8.0 uses the FAO Penman-Monteith method for calculation reference crop evapotranspiration $ET_0$ (Allen et al., 1998). The Penman-Monteith equation is expressed by Eq. 1 as follows:

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} U_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \quad (1)$$

Where $ET_0$ is the reference evapotranspiration (mm/day), $Rn$ is the net radiation (MJ/(m$^2$·d)), $G$ is the soil heat flux density (MJ/(m$^2$·d)), $U_2$ is the wind speed (m/s) at a height of 2 m, $e_s$ is the saturated vapor pressure (kPa), $e_a$ is the actual vapor pressure of the air at standard screen height (kPa), $\gamma$ is the psychrometer constant (kPa/°C), $\Delta$ is the slope of the saturation vapor pressure curve between the average air temperature and dew point (kPa/°C), and $T$ is the mean daily air temperature (°C) (Allen et al., 1998).

The crop evapotranspiration $ET_c$ under standard conditions, is defined as the depth of water needed to meet the water loss through evapotranspiration of a disease-free crop, growing in fields under non-restricting soil conditions including soil water and fertility and achieving full production potential under the given growing environment (Doorenbos and Pruitt, 1977; Doorenbos and Kassam, 1979). $ET_c$ can be calculated using Eq. 2.

$$ET_c = K_c * ET_0 \quad (2)$$

Where $K_c$ is the crop coefficient. See Table 2 for $K_c$ values of the crops utilized.

**Table 2.** $K_c$ values corresponding to the different growing stages for the crops utilized.

| Crop | Stage | | |
|---|---|---|---|
| | **Initial** | **Mid-season** | **Final** |
| | **Kc** | **Kc** | **Kc** |
| **Corn** | 0.7 | 1.2 | 0.6 |
| **Bean** | 0.15 | 1.15 | 0.35 |
| **Oat** | 0.3 | 1.15 | 0.25 |
| **Tomato** | 0.3 | 1.1 | 0.86 |

**Determination of the Design Daily Irrigation Requirement (DDIR)**

Several years of climatic data are required to quantify year-to-year variations in daily $ET$ and precipitation and to evaluate DDIR properly. Thus, the DDIR values were determined for a range of 30 years of daily irrigation requirement (DIR) data for each crop with the corresponding precipitation through each year, and as a second scenario, it was assumed no precipitation at all. DIR's for each year of climatic record were computed with CROPWAT 8.0 utilizing FAO Penman-Monteith equation, climate, soil and crop data as it was previously explained. DDIR usually is less than the peak DIR since some of the water needed to meet the peak DIR can be obtained from the soil. In situations where no water can be obtained from the soil, DDIR equals the peak DIR. In our case, DDIR was determined using Eq. 3.

$$DDIR = \frac{AD}{II_{min}} \qquad (3)$$

Where the *AD* is the allowed depletion of soil water between irrigation (mm), and $II_{min}$ is the minimum irrigation interval during the irrigation season (days). Although *AD* equals typically *RAW* (Readily available water), the *AD* may exceed *RAW* for deficit irrigation strategies. A frequency analysis of several years of DDIR values was required to account for year to year fluctuations in climate. Such an analysis allows us a probability of occurrence to be assigned to each DDIR. For instance, a frequency analysis permits the DDIR that will, on average, be exceeded 10% of the time to be determined.

The return period is often used instead of the probability of occurrence. The relationship between these terms is given in Eq. 4.

$$RP = \frac{100}{P} \qquad (4)$$

Where *RP* is the return period (years) and *P*, the probability of occurrence (percent).

**Frequency analysis**

The first step in a frequency analysis is to have computed DDIR values for each of several years. Next, the probability of occurrence of each DDIR is estimated using Eq. 5.

$$P = \left(1 - \frac{R}{M+1}\right)100 \qquad (5)$$

Where *P* is the probability that a given value will be exceeded in percent, *R* is the rank of DDIR on a list of DDIR values in ascending order (*R* for the smallest DDIR value = 1), and *M* is the number of DDIR values.

A plot of *P* versus DDIR or an extreme value type I (minimum) probability distribution (Haan, 1977) was used to smooth the data for interpolation. A probability distribution transforms *P* so that a linear relationship between the transform of *P* and DDIR results. The Weibull transformation of *P* is shown in Eq. 6.

$$W = log\left[-log\left(\frac{P}{100}\right)\right] \qquad (6)$$

Where *W* is the Weibull transform of *P*.

This study exemplifies a frequency analysis of DDIR data using Eq. 5 and Eq. 6 for the mentioned four crops. DDIR values were exceeded 50, 20, 10, and 5 percent of the time, for return periods of 2, 5, 10 and 20 years, respectively. Thus, the utilization of the frequency analysis to determine design daily irrigation requirements (DDIR) for various return periods was carried out using the following steps for the given 30 years of DDIR values:

1. DDIR data were arranged in ascending order (See results in Table 3).
2. *P* was computed for each DDIR using Eq. 5.
3. *W* was calculated for each DDIR using Eq. 6.
4. *W* was plotted versus DDIR (Fig. 6).
5. *W* values for *P* values were computed in a 50, 20, 10, and 5 percent,
6. DDIR values from the plot for *W* values were read corresponding to *P* values of 50, 20, 10, and 5 percent (2, 5, 10, and 20 year return periods).

## Results and Discussion

### Evapotranspiration using CROPWAT

The modeled daily actual crop evapotranspiration ($ET_c$), and the $ET_0$ at different growth stages were obtained for each year with CROPWAT 8.0 software. Figure 2 shows the $ET_0$ variation during the 30-year analyzed period. We can see the maximum values of $ET_0$ are presented in 1989, 1996, 1998, 2001 and 2010. On the other hand, the minimum values can be seen during the years 1987, 1992, 2004 and 2008. These results are due to the amount of precipitation, fluctuations in the temperature, humidity, wind speed and sunshine hours occurred in each year. Figure 3 shows the Effective Rain variation during the same analyzed period. We can see that the minimum amount of effective rain was in 1989, 1996, 1999, 2008 and 2012. The maximum values for effective rainfall occurred in 1990, 2004, 2007 and 2014.

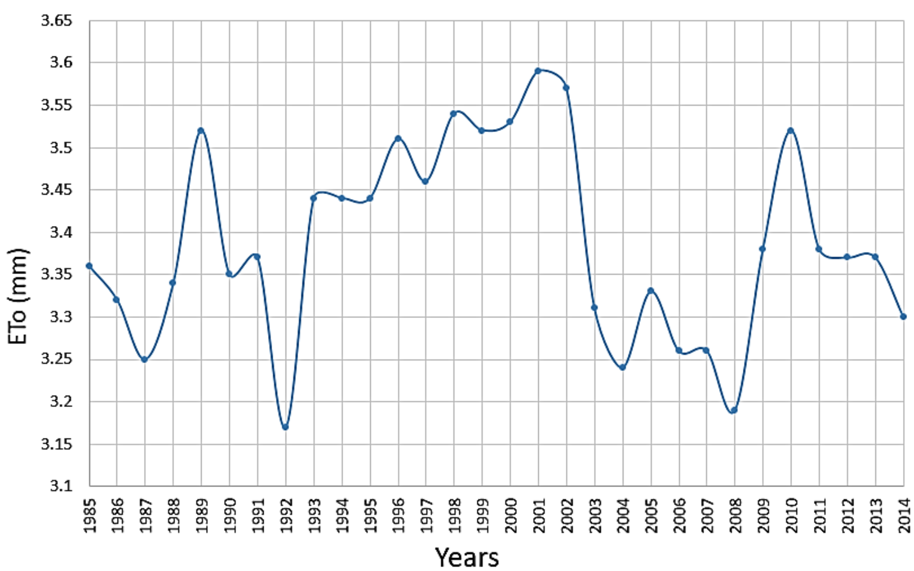


**Figure 2.** $ET_0$ (mm) variation during the 30-year analyzed period.

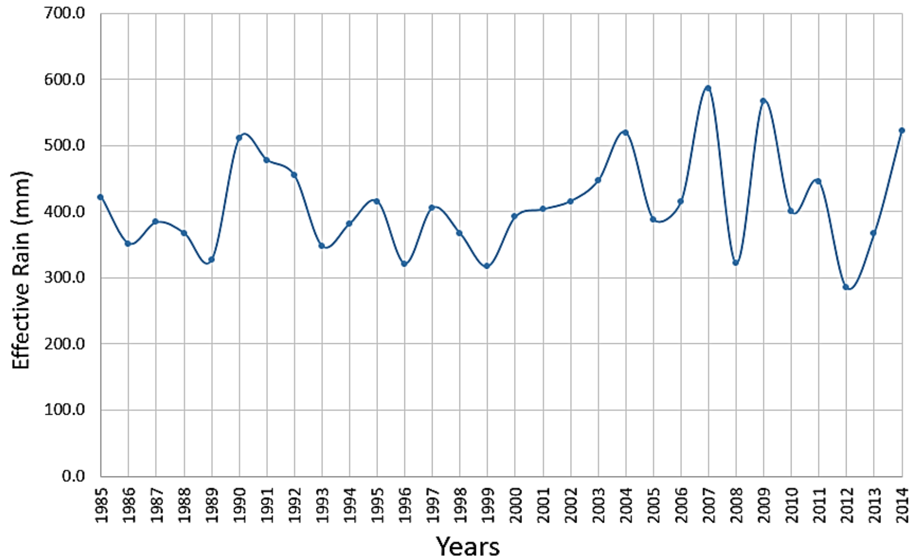


**Figure 3.** Effective Rain (mm) variation during the 30-year analyzed period.

**Design Daily Irrigation Requirement (DDIR)**

In Figure 4 we can see the DDIR (mm/day) variation during the 30-year analyzed period for maize crop with three irrigation systems (surface, sprinkler, and drip). These DDIR values were determined for a range of daily irrigation requirement (DIR) data. DIR's for each year of climatic record were calculated with CROPWAT 8.0 considering precipitation. Similar analysis and calculation of the DDIR during the 30-year period was carried out for the other three crops utilized (bean, oat, and tomato) with the same three different irrigation systems. The impact of the precipitation for design purposes was considered for all the crops and irrigation methods as well. Therefore, DDIR for each crop with the three different irrigation systems was also calculated without precipitation. See Figure 5 for DDIR variation during the 30-year analyzed period without rainfall for the maize crop.

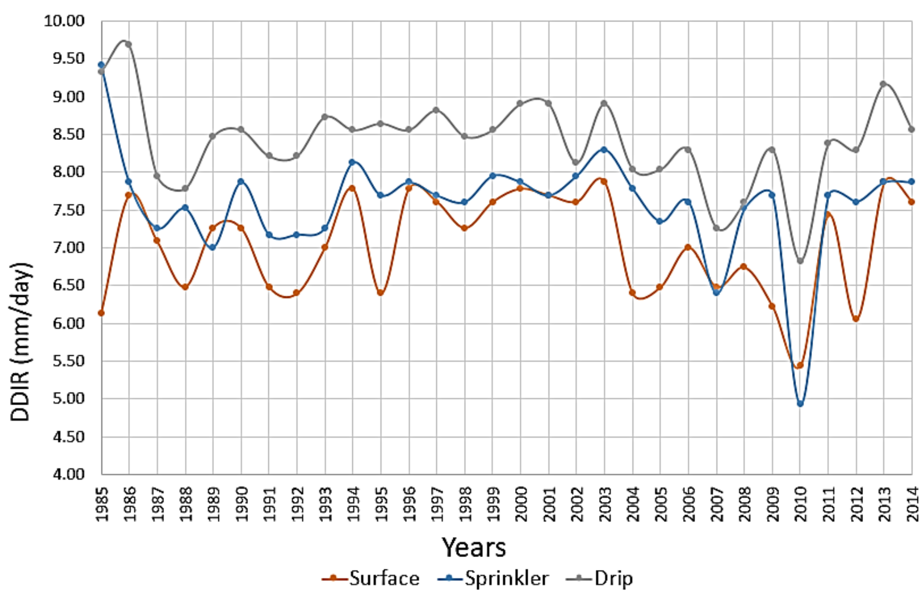

**Figure 4.** DDIR (mm/day) variation during the 30-year period analyzed for maize crop with three irrigation systems (surface, sprinkler, and drip).

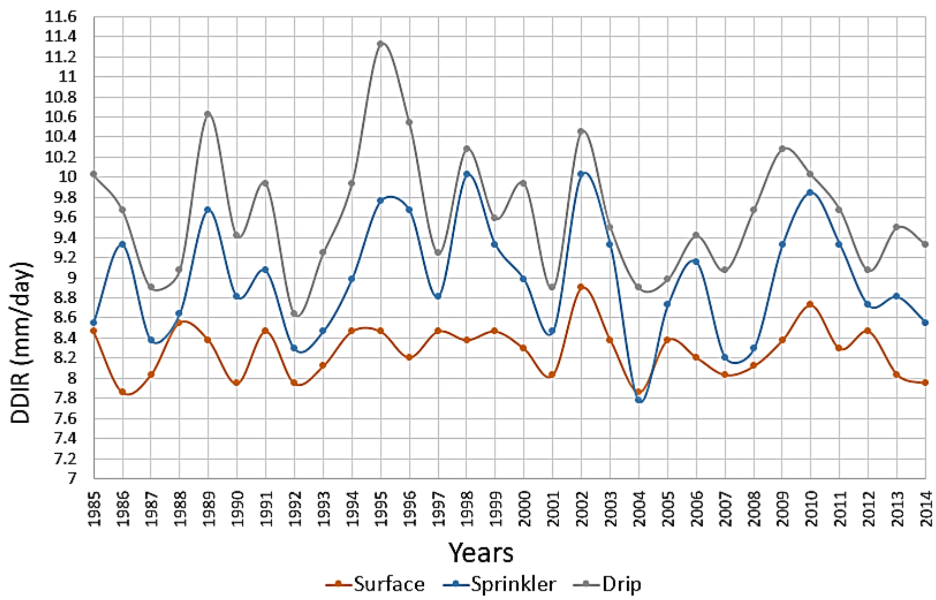


**Figure 5.** DDIR (mm/day) variation during the 30-year period analyzed without rainfall for maize crop with three irrigation systems (surface, sprinkler, and drip).

We can see from Figures 4 and 5 that DDIR (mm/day) values calculated assuming no precipitation are larger than the DDIR values with rainfall for apparent reasons. It is thus necessary to take into account the impact of the precipitation in order to get a rate at which an irrigation system must supply water to achieve the desired level of irrigation without rain.

**Frequency analysis to determine DDIR for various return periods**

The following table summarizes solution steps 1-3 for maize crop irrigated with a surface irrigation system with precipitation. (Similar tables were developed for the other three crops as well as without consideration of precipitation).

**Table 3.** Solution steps 1-3 for maize crop irrigated with surface irrigation.

| DDIR (mm) | Rank (R) | P | RP (years) | W |
|---|---|---|---|---|
| 7.86 | 1 | 96.77 | 1.03 | -1.85 |
| 7.86 | 2 | 93.55 | 1.07 | -1.54 |
| 7.95 | 3 | 90.32 | 1.11 | -1.35 |
| 7.95 | 4 | 87.10 | 1.15 | -1.22 |
| 7.95 | 5 | 83.87 | 1.19 | -1.12 |
| 8.04 | 6 | 80.65 | 1.24 | -1.03 |
| 8.04 | 7 | 77.42 | 1.29 | -0.95 |
| 8.04 | 8 | 74.19 | 1.35 | -0.89 |
| 8.04 | 9 | 70.97 | 1.41 | -0.83 |
| 8.12 | 10 | 67.74 | 1.48 | -0.77 |

| | | | | |
|---|---|---|---|---|
| 8.12 | 11 | 64.52 | 1.55 | -0.72 |
| 8.21 | 12 | 61.29 | 1.63 | -0.67 |
| 8.21 | 13 | 58.06 | 1.72 | -0.63 |
| 8.29 | 14 | 54.84 | 1.82 | -0.58 |
| 8.29 | 15 | 51.61 | 1.94 | -0.54 |
| 8.38 | 16 | 48.39 | 2.07 | -0.50 |
| 8.38 | 17 | 45.16 | 2.21 | -0.46 |
| 8.38 | 18 | 41.94 | 2.38 | -0.42 |
| 8.38 | 19 | 38.71 | 2.58 | -0.38 |
| 8.38 | 20 | 35.48 | 2.82 | -0.35 |
| 8.47 | 21 | 32.26 | 3.10 | -0.31 |
| 8.47 | 22 | 29.03 | 3.44 | -0.27 |
| 8.47 | 23 | 25.81 | 3.88 | -0.23 |
| 8.47 | 24 | 22.58 | 4.43 | -0.19 |
| 8.47 | 25 | 19.35 | 5.17 | -0.15 |
| 8.47 | 26 | 16.13 | 6.20 | -0.10 |
| 8.47 | 27 | 12.90 | 7.75 | -0.05 |
| 8.55 | 28 | 9.68 | 10.33 | 0.01 |
| 8.73 | 29 | 6.45 | 15.50 | 0.08 |
| 8.90 | 30 | 3.23 | 31.00 | 0.17 |

The solution of step 4 is shown in Figure 6, in which shows a plot of the *W* values versus the DDIR values for the 30-year period under analysis.

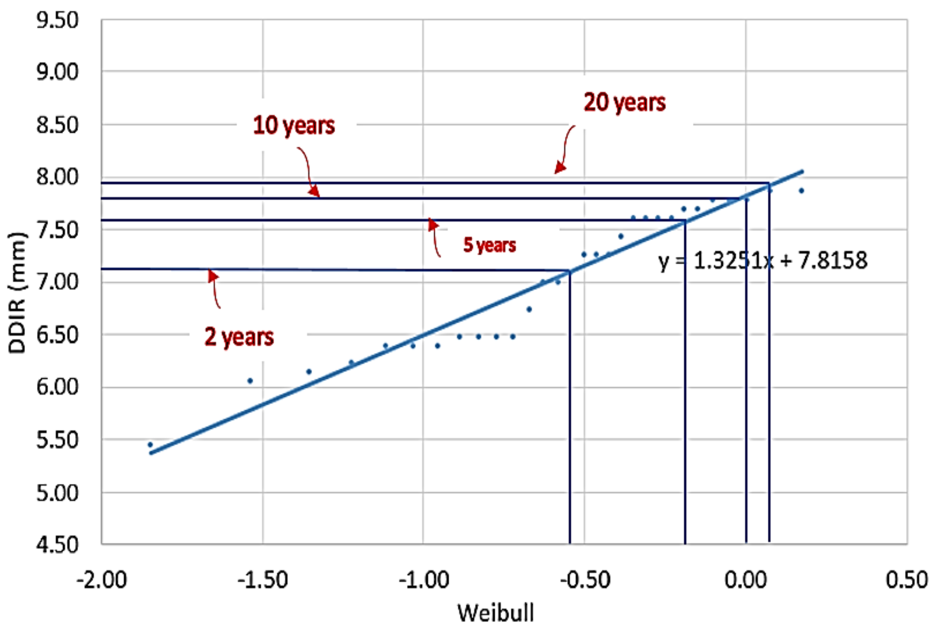


**Figure 6.** Solution to step 4. *W* versus DDIR for the 30-year period.

Given the 30 years of DDIR values for maize crop irrigated with a surface irrigation system and considering precipitation we found the results as follows:

Solution for step 5

W for (P = 50%) = -0.52

W for (P = 20%) = -0.16
W for (P = 10%) = 0
W for (P = 5%) = 0.11

Solution step 6
DDIR for:
P = 50% (RP = 2 years) = 7.17 mm/day
P = 20% (RP = 5 years) = 7.68 mm/day
P = 10% (RP = 10 years) = 7.77 mm/day
P = 5% (RP = 20 years) = 7.86 mm/day

Similar results of all the steps described in the methodology were obtained for each of the other three crops (bean, oat, and tomato). Table 4 shows the DDIR values that will be exceeded 50%, 20%, 10% and 5% of the times, for return periods of 2, 5,10, and 20 years respectively for the maize crop considering precipitation (as in the results shown above) and DDIR values without considering rainfall. Tables 5, 6 and 7 show DDIR values that will be exceeded 50%, 20%, 10% and 5% of the times, for return periods of 2, 5,10, and 20 years respectively for bean, oat, and tomato crops correspondingly.

**Table 4.** DDIR values that will be exceeded 50%, 20%, 10% and 5% for maize crop

| **Maize DDIR (mm/day)** | | | | |
|---|---|---|---|---|
| **Precipitation** | | | | |
| **P** | **50%** | **20%** | **10%** | **5%** |
| **W** | **-0.52** | **-0.16** | **0** | **0.11** |
| **RP (years)** | **2** | **5** | **10** | **20** |
| **Surface** | 7.17 | 7.68 | 7.77 | 7.86 |
| **Sprinkler** | 7.68 | 7.86 | 8.10 | 8.79 |
| **Drip** | 8.46 | 8.88 | 9.10 | 9.13 |
| **Without Precipitation** | | | | |
| **P** | **50%** | **20%** | **10%** | **5%** |
| **W** | **-0.52** | **-0.16** | **0** | **0.11** |
| **RP (years)** | **2** | **5** | **10** | **20** |
| **Surface** | 8.33 | 8.46 | 8.54 | 8.80 |
| **Sprinkler** | 8.89 | 9.60 | 9.84 | 10.02 |
| **Drip** | 9.54 | 10.22 | 10.53 | 10.93 |

**Table 5.** DDIR values that will be exceeded 50%, 20%, 10% and 5% for bean crop.

| **Bean DDIR (mm/day)** | | | | |
|---|---|---|---|---|
| **Precipitation** | | | | |
| **P** | **50%** | **20%** | **10%** | **5%** |
| **W** | **-0.52** | **-0.16** | **0** | **0.11** |
| **RP (years)** | **2** | **5** | **10** | **20** |
| **Surface** | 5.05 | 5.35 | 5.67 | 5.74 |
| **Sprinkler** | 6.13 | 6.54 | 6.73 | 6.73 |
| **Drip** | 7.17 | 7.32 | 7.43 | 7.72 |

| Without Precipitation | | | | |
|---|---|---|---|---|
| **P** | **50%** | **20%** | **10%** | **5%** |
| **W** | **-0.52** | **-0.16** | **0** | **0.11** |
| **RP (years)** | **2** | **5** | **10** | **20** |
| **Surface** | 6.04 | 6.79 | 6.91 | 6.98 |
| **Sprinkler** | 6.82 | 7.08 | 7.25 | 7.91 |
| **Drip** | 7.77 | 8.57 | 8.96 | 9.27 |

**Table 6.** DDIR values that will be exceeded 50%, 20%, 10% and 5% for oat crop.

| Oat DDIR (mm/day) | | | | |
|---|---|---|---|---|
| **Precipitation** | | | | |
| **P** | **50%** | **20%** | **10%** | **5%** |
| **W** | **-0.52** | **-0.16** | **0** | **0.11** |
| **RP (years)** | **2** | **5** | **10** | **20** |
| **Surface** | 9.73 | 9.76 | 9.84 | 9.86 |
| **Sprinkler** | 11.31 | 11.49 | 11.56 | 11.70 |
| **Drip** | 12.05 | 12.52 | 12.67 | 12.82 |
| **Without Precipitation** | | | | |
| **P** | **50%** | **20%** | **10%** | **5%** |
| **W** | **-0.52** | **-0.16** | **0** | **0.11** |
| **RP (years)** | **2** | **5** | **10** | **20** |
| **Surface** | 9.76 | 9.83 | 9.89 | 9.92 |
| **Sprinkler** | 11.35 | 11.53 | 11.60 | 11.77 |
| **Drip** | 12.18 | 12.68 | 12.87 | 12.96 |

**Table 7.** DDIR values that will be exceeded 50%, 20%, 10% and 5% for tomato crop.

| Tomato DDIR (mm/day) | | | | |
|---|---|---|---|---|
| **Precipitation** | | | | |
| **P** | **50%** | **20%** | **10%** | **5%** |
| **W** | **-0.52** | **-0.16** | **0** | **0.11** |
| **RP (years)** | **2** | **5** | **10** | **20** |
| **Surface** | 7.51 | 8.20 | 8.46 | 7.65 |
| **Sprinkler** | 7.77 | 8.10 | 8.44 | 8.92 |
| **Drip** | 9.46 | 9.74 | 9.84 | 9.90 |
| **Without Precipitation** | | | | |
| **P** | **50%** | **20%** | **10%** | **5%** |
| **W** | **-0.52** | **-0.16** | **0** | **0.11** |
| **RP (years)** | **2** | **5** | **10** | **20** |
| **Surface** | 7.77 | 8.27 | 8.85 | 8.89 |
| **Sprinkler** | 7.80 | 8.93 | 8.94 | 8.98 |
| **Drip** | 9.50 | 9.80 | 9.92 | 9.97 |

This frequency analysis of 30 years of DDIR values is useful to account for year to year fluctuations in climate. Such analysis allowed a probability of occurrence to be assigned to each DDIR obtained during that period. For example, as it is shown in the previous tables, the frequency analysis enables the DDIR that will, on the average, be exceeded 10 percent of time to be determined. To interpret the results obtained, we know that a

50% probability of occurrence is equivalent to a 2-year return period. A 2-year return period DDIR for each crop with a different irrigation system means that the DDIR will be, on the average, exceeded once in 2 years but does not guarantee it. It may be exceeded in each of the 2 years or not at all. A 2-year return period indicates that historically, the DDIR has, on average, been exceeded once in 2 years. For instance, the value of DDIR=5.05 mm/day for a bean crop irrigated with surface irrigation for a 2-year return period and 50% of probability of occurrence means that the 5.05 mm/day will be, on average, surpassed every 2 years. Similar analysis can be derived for a 20% probability of occurrence which is equivalent to a 5-year return period. A 5-year return period DDIR means that the DDIR will be, on the average, exceeded once in 5 years. A 10% probability of occurrence is equivalent to a 10-year return period. A 10-year return period DDIR signifies that the DDIR will be, exceeded once in 10 years. In the same way, a 5% probability of occurrence is equivalent to a 20-year return period. A 20-year return period DDIR indicates that the DDIR will be, exceeded once in 20 years.

In addition, we can notice that the maximum values of DDIR are found on drip irrigation systems, followed by sprinkler irrigation, and finally surface irrigation. This is because of the interval between irrigations. The average daily irrigation requirement is smallest for longer irrigation intervals, i.e., intervals in surface irrigation systems. The irrigation intervals with surface irrigation systems are 30 days for maize crop according to the irrigation practices carried out in Texcoco, Mexico. Intervals for sprinkler irrigation usually range 15 to 20 days, while for drip irrigation the intervals are of 3 to 5 days. Another factor to consider is the crop's sensitivity to water stress and critical depletion fractions. For example, DDIR values for tomato are larger than maize and bean DDIR values, irrigated as well with surface irrigation methods. As it was stated earlier, we can see that the DDIR values for the simulations without precipitation are larger than the DDIR values considering rainfall for obvious reasons.

## Conclusions

The analysis of the effect of the irrigation system on the estimation of the maximum irrigation requirements was carried out for design purposes in four different crops cultivated in Texcoco, Mexico, to take account what is the peak demand required to dimension the water network during critical conditions, considering the impact of the precipitation. The Design Daily Irrigation Requirements (DDIR) were determined from several years of daily irrigation requirement data obtained with the software CROPWAT, and then a frequency analysis of 30 years DDIR values were made to account for year-to-year variations in climate. Such analysis allowed us to get a probability of occurrence to be assigned to each DDIR.

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