CANAL CAPACITIES FOR DEMAND UNDER SURFACE IRRIGATION

By Albert J. Clemmens, M. ASCE

Abstract: Providing water to users on demand usually requires an increase in canal capacity over the same volume of water delivered at a uniform rate. A simulation model was used to develop demand patterns for hypothetical surface irrigation conditions. These results were used to determine the canal capacity required to meet various levels of demand. A modification to these results was hypothesized to be appropriate for delivery schedules where delivery is arranged. These results are expressed in simple, nondimensional terms and compared to capacities for continuous flow and rotation systems and to capacities from Clement's demand formulas. It is shown that Clement's formulas which were developed for sprinkler irrigation are inappropriate for surface irrigation demand since they do not account for the wide variations in possible conditions. Results are particularly inappropriate for small relative service areas. Simple canal capacity equations were developed for demand and arranged surface irrigation distribution systems for a 90% level of service (i.e., water is available 90% of the time when demanded).

Introduction

Some irrigation projects are built to supply water to farms that apply water with surface irrigation methods. Water is often distributed to farmers within the project through a network of canals. Canals are used because they can be constructed more inexpensively than other available methods and because local labor and materials can be used. The simplest method of distributing water in a canal network is to supply a continuous flow of water to each farmer. The farmer is then responsible for distributing this water over different parts of his farm. This continuous flow system is simple to operate because once flow into the canal system is set, it does not change. However, since plants use water at different rates over the growing season, a continuous flow system would supply too much water early in the season and perhaps not enough water later in the season. Where available water is in short supply, this type of inefficiency is not reasonable. Some continuous flow systems adjust the supply flow rate periodically to try to more closely match plant water needs.

For surface irrigation, it is not practical to supply water at the rate at which the plants need water. For example, plants may use water at a rate of 2–10 mm/day, whereas surface irrigation systems generally are designed to apply from 50–150 mm/irrigation, which will generally be applied in a period of 1–48 hrs. This is dictated by soil water holding capacities, root zone depths, soil infiltration rates, and efficient irrigation stream sizes. Thus to achieve even a reasonable efficiency, an available


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ir. A stream must be rotated between different areas of land. If a farm land area is large enough, he may be able to handle a continuous flow, otherwise it is more practical to rotate the available irrigation stream among neighboring farmers. Operation of the canal distribution system for a rotation system does not change from that of a continuous flow system except where water is actually turned into the farms. Rotation systems may also be inefficient if inflows are not adjusted through the season to match plant water requirements.

If the same stream that was once split among eight farmers, for example, is now given to one farmer one day out of eight days, his farm canals and the structure which turns water out of the project supply canal must be able to handle eight times the flow rate. However, the entrance canal capacity which brings water to these eight farmers has not changed in size. Now if farm water use efficiencies (water required/water delivered) have been improved, the farm canal size could be reduced somewhat from the eight-fold increase. In addition, this increase in efficiency could potentially reduce the size of the project supply canal. A change in delivery method, while it may require larger canals on the farm, can improve efficiency and may also result in smaller project supply canals or a larger project area being serviced.

Surface irrigation systems are generally designed to be efficient within a small range of application depths. Since crop water use rates vary widely over the season, the period between irrigations should also change. Thus, variations in frequency rather than flow rate are necessary to adjust a rotation schedule to match plant needs for surface irrigation. An adjustable frequency rotation system is somewhat difficult to develop. In addition, variations in soil characteristics and differences in crop selections will cause different fields within a rotation unit to require different rotation intervals during the same part of the season, a nearly impossible task even for an adjustable frequency rotation scheme.

It has been known for several decades that to be efficient in water use and productive in yields, the delivery system must be flexible in rate, frequency and duration (6). An extreme case of this flexibility is a demand system where any quantity of water is delivered whenever desired for any duration desired. Obviously such systems must operate within some practical bounds, e.g., within a range of flow rates and within an overall seasonal water allocation. Returning to our example of the eight farmers serviced by one project supply canal, if all eight demanded water at the same time, the supply canal to those eight farmers would have to be eight times as large as for a rotational system. If each farmer wanted double the usual flow, say for half the duration, the canal would have to be 16 times as large. One alternative is to use farm reservoirs to accept water given in rotation, and apply it when needed. Another alternative is for farmers to arrange water deliveries in an effort to reduce the amount of overlap in demand. In real situations, the probability that all eight farmers would want water at the same time would be fairly low.

Arranged delivery schedules are used in many irrigation districts in the western U.S. Typically water is ordered from one to three days ahead of time. Flow rates are generally limited by structure and canal capacities. Durations are either continuously variable or set to fixed intervals such as 12 or 24 hrs. Replege and Merriam (6) have listed a number of categories of delivery schedules in terms of constraints applied on rate, frequency, and duration.

Several questions come to mind regarding canal capacities: How large a canal is necessary for a demand system, for example, if you want to be able to supply demand, say, 70 or 80% of the time? How is this overlap in demand mitigated by arranged schedules? What should canal capacities be under these circumstances? This paper discusses these issues and presents analytical results from computer simulation in an attempt to provide useful methods for determining canal capacities for demand and arranged delivery schedules.

**Canal Capacity Relationships**

Canal capacities are based on the peak water use period and on the land area which they service. The peak water use rate, \( W_* \), is defined as the peak consumptive use in volume per unit area per unit time divided by the irrigation efficiency. It represents the amount of water to be delivered. Now, given a turnout delivery flow rate \( Q_t \), which is established as an average (or maximum) for design of farm turnouts, the area, \( A_t \), that can be serviced by a continuous flow system would be

\[
A_t = \frac{Q_t}{W_*} \tag{1}
\]

with appropriate units conversion. This is also the area serviced by a single rotation of a rotation system. If this area is broken up into \( N \) fields (or farms) each with area \( A_i \) which is serviced by one turn in the rotation from a single turnout with capacity \( Q_t \), then the rotation frequency

\[
F = \frac{1}{N} \cdot \frac{A_i}{A_t} \tag{2}
\]

It is useful to define these variables in relative terms. The flow rate of a canal, \( Q \), is referenced to the average turnout design flow rate, \( Q_t \), to give a relative flow rate

\[
Q_a = \frac{Q}{Q_t} \tag{3}
\]

Similarly, the size of a canal service area, \( A_s \), is referenced to the rotation unit size, \( A_t \), to give a relative service area \( A_s \)

\[
A_s = \frac{A}{A_t} = \frac{Q}{Q_t} = Q_a \tag{4}
\]

From Eqs. 1, 3, and 4 for a rotation or continuous flow system, we get

\[
A_s = \frac{A}{A_t} = \frac{W_*}{Q_t} = \frac{Q}{Q_t} = Q_a \tag{5}
\]
since \( \dot{A} = \dot{q} \), which is analogous to Eq. 1.

If the area divided, \( A_r \) is equal to a rotation area, \( A_r = 1 \). From Eq. 4 for rotation and continuous flow systems, \( Q_r = 1 \) as well. Operation of demand and arranged delivery schedules will require \( Q_r > 1 \). But how much greater? Twice as much? Irrigation projects which deliver water in a similar manner, but with different crop consumptive use values and different delivery flow rates would be expected to need similar proportionate increases in canal capacities. Thus \( A_r \) and \( Q_r \) are convenient for analyzing the changes in canal capacity required for flexible (arranged and demand) delivery over that for the rigid (continuous flow or rotation) delivery schemes.

**Clement’s Demand Formulas**

Clement (1) developed two formulas for analyzing the demand requirements for irrigation. These formulas were developed for an irrigation project which used primarily sprinkler irrigation. Thus a particular field delivery point has flow either on or off for a given day. Given that there are \( R \) delivery points, the first demand formula is used to find the system capacity in terms of the number of users \( N \) such that the probability that \( N \) or fewer users will be using the system simultaneously is greater than some desired probability \( P_x \). This is a supplier-oriented view since it considers a time-based frequency of meeting capacity, (that is, the portion of time that the capacity is sufficient). Thus \( P_x \) is a time-based service measure. The second demand formula finds the system capacity \( N \) such that the probability of the user finding the system at capacity or busy when (s)he wants water (congestion) is less than some desired probability, \( P_x \). This is a more user-oriented view since it considers a use or demand frequency of having insufficient capacity, (i.e., how often is service available when it is demanded?). Thus, \( P_x \) is a demand-based service measure. Clement’s first demand formula is

\[
N = R_p + U' \sqrt{R p q} \tag{6}
\]

in which \( N \) = number of users; \( R \) = total number of delivery points; \( p \) = average frequency of irrigation, \( q = 1 - p \); and \( U \) is defined from \( P_x = \pi(U) \) in which the function \( \pi = \) the normal cumulative distribution function. This equation was derived by initially assuming that the probability of a particular farm unit being operated during a given day is described by a binomial probability distribution. A binomial distribution assumes that the probability of irrigating a given field on any particular day is independent of the past history of irrigations. This says that an irrigation would be just as likely today if we irrigated yesterday or a week ago. This does not seem reasonable for surface irrigation, nor for sprinkler irrigation in many areas. Next, it was assumed that if \( R \) was large, the binomial distribution could be approximated with a normal distribution. This approximation is appropriate only for \( R p > 5 \) (7). This formula supplies continuous values of \( N \) while in general, capacities are usually discrete multiples of the delivery rate. Clement’s second demand formula is given by

\[
N = R_p + U' \sqrt{R p q} \tag{7}
\]
the first demand formula for \( R < 100 \) and the second for \( R > 100 \). When demand is greater than capacity this excess demand must be handled in later periods. However, no adjustments were made for users who could not receive service. Clement recommends that the second formula (Eqs. 7 and 8) be used with \( P_s = 0.01 \). This also applies to the first formula (Eq. 5) where the \( P_s \) must be very high, say 0.99. Appropriate levels of performance are discussed in a later section.

Clement’s formulas can be written in the terminology of the previous section since by definition \( R = A_t / A_n F, N = Q_n, P = F, q = 1 - F \), where Clement’s terms are stated to the left of the equal sign. Eqs. 6, 7 and 8 become, respectively

\[
Q_n = A_n + U \sqrt{A_n (1 - F)} \tag{9}
\]

\[
Q_n = A_n + U' \sqrt{A_n (1 - F)} \tag{10}
\]

\[
P_s \sqrt{A_n (1 - F)} = \frac{\psi(U')}{\pi(U')} \tag{11}
\]

Thus the second term in Eqs. 9 and 10 represent the excess capacity needed for a demand delivery capability.

These formulas give the instantaneous canal capacity required at a given point in the system. Below any given bifurcation, the required capacity would decrease since the service area is reduced.

The binomial (and then assumed normal) distribution used in the development of these formulas which were derived for sprinkler irrigation systems do not appear to be appropriate for surface irrigation. Also, Clement’s formulas are meant to apply only for relatively large scale systems \((A_n > 5)\) and for large performance measures (congestion of 1%). However, lesser performance levels may be more appropriate for surface irrigation systems, particularly where arranged schedules are used. A simulation model was developed to simulate the demand for water under surface irrigation in order to test Clement’s formula and to determine what actual demand capacities are needed.

**Surface Irrigation Demand Simulation**

To develop statistical relations between area serviced and canal capacity for a demand system, a long record of actual demand patterns for a variety of crops, soils, irrigation strategies, etc., must be obtained. However, since very few actual demand systems exist, historical data is not available from which to make these predictions. An alternative is to generate demand patterns from simulations. There were three steps taken in this simulation process. First, weather data were generated to simulate variations in climatic conditions. Historical records could also have been used. Second, daily evapotranspiration (ET) was simulated based on climatic conditions and available soil water. Irrigation soil depletion strategies then were used to determine when to refill the root zone. This gave a series of irrigation events for each simulation year. This step was repeated for a variety of crops, soils and irrigation strategies, each representing a single field. Finally, individual fields were randomly selected in combinations to produce a distribution of demands for different numbers of fields.

Weather data for a 20-yr simulation were developed with the program WGEN (Weather Generator) based on the climate at Phoenix, Arizona (5 and “WGEN: A Model for Generating Daily Weather Variables,” by C. W. Richardson and P. A. Wright, USDA/ARS, Grasslands, Soil and Water Research Laboratory, Temple, Tex., 1984, unpublished).

This model did a good job of simulating Phoenix weather (Ref. 5 for details). An arid climate was chosen because it is more typical of areas which are water short and in need of conservation measures. The CREAMS (Chemicals, Runoff and Erosion from Agricultural Management Systems) model (4), as modified by Reinhik (5) to provide different irrigation strategies, was used to develop irrigation schedules for each of 60 fields each year. CREAMS was selected since it simulates changes in soil moisture storage and predicts ET from crop and soil data.

The 60 fields consisted of combinations of 4 crops as shown in Table 2, five soils with varying water holding capacities as shown in Table 3, and 3 depletion levels, namely 45, 55 and 65% of available water, at which irrigation was initiated. CREAMS uses daily values of water use so that only the day of irrigation and the depth to refill the root zone is given as output. The crops were chosen to give a wide variety of consumptive use patterns and still be typical of crops grown in the area. The input to CREAMS (rooting depths and leaf area index) was adjusted to give consumptive use values in agreement with those published by

<table>
<thead>
<tr>
<th>TABLE 2.—Crops Used in CREAMS Model with Rooting Depths as Input and Resulting Consumptive Use over the 92-Day Period of June, July and August</th>
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<tbody>
<tr>
<td>Crop (1)</td>
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<tr>
<td></td>
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<tr>
<td>Alfalfa</td>
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<tr>
<td>Cotton</td>
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<td>Citrus</td>
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<td>Sorghum (double cropped)</td>
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<tr>
<th>TABLE 3.—Soils Chosen and Water Holding Capacities for Input to CREAMS Model</th>
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<tr>
<td>Soil type (1)</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Loamy sand</td>
</tr>
<tr>
<td>Sandy loam</td>
</tr>
<tr>
<td>Very fine sandy loam</td>
</tr>
<tr>
<td>Loam</td>
</tr>
<tr>
<td>Silty clay loam</td>
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demand for the canal over the 24-hr period, thus depth applied would have a significant influence. The second was based strictly on number of fields being irrigated on a particular day, and thus represented discrete increments of demand. The statistics collected included the time-based frequency of demand at a series of capacities and the demand-based frequency at the same series of capacities. From this, the capacity representing a particular value of cumulative frequency could be determined for comparison with Clement's formula.

There is some question about the appropriateness of time-based frequency of having sufficient capacity (i.e., percent of time that the capacity is not exceeded) as a service measure. For example, if a field is irrigated one day out of ten \( F = 0.1 \) on the average, then the farm canal will not be in use 90% of the time \( P_s = 0.9 \). For the simple statistics used here, a capacity of zero would satisfy the demand for any service measure, \( P_s < 90\% \). A relative frequency, \( P_s \), was developed to adjust, \( P_r \), for this problem. When \( A_r < 1 \), \( A_n \) is also the expected time a canal with \( Q_s = 1 \) is busy. \( P_r \) is found from the relation

\[
A_n = \frac{1 - P_s}{1 - P_r} \quad A_r < 1 \quad \text{(12)}
\]

Now the time-based frequency is found relative to the expected busy time rather than total time. Suppose for example, \( A_n = 0.5 \) and \( P_s = 80\% \). From Eq. 12, solving for \( P_r \):

\[
P_r = 1 - \frac{1 - P_s}{A_n} = 1 - \frac{1 - 0.80}{0.5} = 0.60
\]

Thus the computed capacity will be adequate only 60% of the time that the canal is expected to be in service.

**Results**

The results of the simulation model for a time-based service frequency (that is, percent of time capacity not exceeded) of 80% is shown in Fig. 2 for continuous variations in capacity. Also for \( P_s = 80\% \), simulation results are presented for both discrete and continuous capacities with results also shown for capacity with idle time removed \( (A_r < 1) \). For \( P_s = 95\% \), continuous simulation results and Clement's first formula are shown for \( A_r > 1 \), and adjusted simulation results are shown for \( A_r < 1 \). Canal capacities for continuous flow and rotation systems are also shown. Values obtained from the simulation model with variations in applied depth and from Clement's first formula are in very close agreement over the entire range. This indicates that the assumptions used to develop this formula are reasonable even for surface irrigation. (However, there is some serious question about a time-based service frequency as a service measure.) Note that below a relative service area of approximately \( A_r = 0.45 \), the relative canal capacity drops below one. The canal capacities for the relative time-based frequency, \( P_r \), are also shown in Fig. 2. This form of time-based frequency is more user oriented

FIG. 1.—Representative Consumptive Use during Peak Use Period of June, July and August (Days 152 to 243) for the Four Crops Used in the Simulation

Eric, et al. (3), (see Table 2 and Fig. 1). Soils were chosen to represent a variety of water holding capacities (Table 3).

The fields were taken in groups of two, three, four, etc., up to 60 in groups by which 60 is evenly divisible in order to simulate canals with different downstream service areas. This was done day by day during the peak use period of June, July, and August (Days 152-243) for each year of the 20-yr simulation for a total of 1,840 days. The order (and thus groupings) of fields was chosen randomly. The average depth applied per irrigation was 113 mm (4.45 in.) with a standard deviation of 42 mm (1.65 in.). No adjustment was made for efficiency since only relative numbers are of significance. The average interval between irrigations was 16.3 days \( F = 0.061 \), the standard deviation of average interval for the sites was 10.7 days. For the 60 sites, there was an average of 3.43 irrigations per day or 6,311 irrigations over the 92-day interval for 20 yrs.

Two sets of output statistics were collected. The first set represents continuous variations in demand. It was based on spreading the total
as shown by the increased capacity.

The simulation model results for demand with discrete variations in capacity are also shown in Fig. 2, where only the number of fields being irrigated is of concern. Note that the line for continuous variations in demand falls through the middle of the stair stepping pattern. Note also that the stair stepping pattern for demand is shifted to the left of the

FIG. 4.—Comparison of Canal Capacities for Demand-Based Service Levels of 50, 60, 90 and 95% from Simulation and from Clement's Second Formula

stair stepping pattern for a rotation system. This would indicate that canal capacities would only need to be increased over part of the distribution system. Also shown in Fig. 2 are the adjusted simulation results for $P_d = 95\%$ along with Clement's first formula over part of the range for comparison. Agreement is not as good here as it was at $P_d = 80\%$.

The results of the simulation for a demand-based service frequency are shown in Fig. 3 along with Clement's second formula. The capacities from the simulation model at an 80% service level are significantly higher than Clement's formula. This is not too surprising since Clement's formula does not consider any variations in quantity or depth delivered to each user. The increased capacity caused by depth variations can be removed from the results if the distribution of depths is known. A cumulative probability of 80% for this distribution occurs at 147.33 mm (5.8 in.). Thus the capacity for a uniform application (and the same timing distribution) would be in direct proportion to the mean or $(113/147.3) \times 100 = 76.7\%$ of the simulation output. These values are plotted in Fig. 3 and show much better agreement with Clement's formula, particularly at high $A_r$ values. The stair stepping pattern for discrete demand is to the left of Clement's formula, again indicating the effect of variations in demand quantity. Note also that capacities for Clement's formula drop below unity, while for the simulation they do not.

A comparison of the demand-based results of the simulation and Clement's formula for demand service levels of 50, 80, 90 and 95% are shown in Fig. 4. The simulation results are considerably different from Clement's second formula throughout the entire range.

ANALYSIS

Discrete versus Continuous Capacities.—It was noted earlier that all
the simulation results show \( Q_n \) values greater than unity while Clement's formulas show values of \( Q_n \) less than unity. A relative canal capacity of 1 would normally be used with a rotation system. In fact, for a strict rotation system, canal capacities would be in discrete increments of the delivery rate, \( Q_n \), or would be integer values of \( Q_n \). Thus, rather than the straight line (i.e. \( Q_n = A_n \)) of a continuous flow system, a strict rotation system would have a stair stepping pattern. In this case as \( A_n \) approaches zero, \( Q_n \) approaches one. This pattern is shown in all the simulation results, even though this was not stipulated as a requirement. This makes sense since even the smallest area to which water is delivered should receive the design delivery rate. For Clement's formulas, \( Q_n \) approaches zero as \( A_n \) approaches zero. Thus, Clement's formulas are not appropriate below \( A_n = 1 \). However, it may be appropriate to design canals in noninteger multiples of \( Q_n \) for arranged and demand delivery systems. If the delivery flow rate is fixed by policy, then it is not appropriate. However, if flexibility in flow rate is allowed, then it makes sense since the farmers can order a flow rate which is efficient for the current conditions. In some cases it may be above \( Q_n \), and in others it may be below \( Q_n \).

**Efficiency Considerations.**—It should be emphasized that arranged and demand schedules can often result in higher farm irrigation efficiencies. This, of course, depends upon the capabilities of the farmers. Increasing flexibility can make canal operations more difficult resulting in lower conveyance efficiencies caused by the inability to uniformly distribute water. Automatic controls can greatly reduce this problem. Without automatic controls, conveyance losses due to regulation (not seepage) for nonautomated canal systems with arranged schedules are on the order of 10–15% (2). This is generally as good as water is distributed in most rotation systems. In general, the increase in efficiency on farm will offset the increase in relative canal capacity. The tendency is for larger delivery rates, larger quaternary canals, slightly larger tertiary canals and smaller main canals when comparing flexible (arranged) to rigid (rotation) schedules.

**Effects of Congestion.**—This analysis has ignored the fact that when congestion occurs, those waiting for service potentially can cause more congestion in later periods. Thus the actual congestion is higher. We can assume that by selecting a capacity with a simple probability of 1% congestion, increased congestion by this 1% will be negligible. However, for a capacity at a simple probability of 50%, increased congestion is certain to be significant and the actual congestion higher than 50%. This makes the true capacity required for 50% demand service higher than indicated here, thus bringing these capacity curves farther apart. The magnitude of this shift in capacity has not been evaluated here.

**Arranged Schedules.**—The nature of demand is influenced by specific site conditions. If capacities are based on supplying water for 24-hr periods, 7 days a week and irrigators will only work daylight hours, 5 days a week, the canals will probably not be capable of meeting the demand. More serious is the problem of controlling a canal system under this form of demand, but this is beyond the scope of this paper. Such practical considerations, however, often make arranged delivery schedules more practical for surface irrigation than demand schedules.

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**FIG. 5.**—Canal Capacities for Service Levels of 80 and 95% for Supply-Based Service Levels Adjusted for Demand (ADJ SUPPLY) and for Demand-Based Service Levels Adjusted for Supply (ADJ DEMAND) from Simulation.

Arranged schedules are used to reduce the capacity requirements of a demand schedule and to allow supply-oriented operation of canals. Arranged schedules are a combination of supply and demand oriented systems. Different arrangement schemes allow different types and degrees of flexibility. Earlier, the time-based service capacities were adjusted to account for canal nonuse periods, a more demand-oriented approach. Also, demand capacities were reduced by removing the fluctuations in quantities ordered, a more supply-oriented approach. The results of these two approaches is shown in Fig. 5 for 80 and 95% service measures. These two approaches are in reasonably close agreement on required canal capacity, being different mixtures of supply and demand orientation. Thus it may be reasonable to use these adjusted demand capacities for arranged delivery systems.

**Appropriate Service Levels.**—It is difficult to judge what level of service or performance is necessary for the efficient operation of a canal system. It may be useful to compare these results with the actual capacities of existing irrigation projects with flexible delivery schedules. Fig. 6 shows data from two different canal systems: the Salt River Project (SRP) in central Arizona and the Wellton-Mohawk Irrigation and Drainage District (W-M) in southwestern Arizona. Data for SRP was taken from laterals from the Eastern Canal for 1978 acreages (2). The high relative capacities are partially due to land which has been taken out of production by urban growth. However, SRP capacities are still significantly higher than W-M capacities. SRP operates on a more flexible schedule than W-M with 1-day rather than 3-day lead times and fewer conflicts in arrangements.

However, with 3-day lead times, delivery within ±1 day can allow arrangements to reduce peak demand. This is not meant to imply that arranged schedules require long lead times. The arranged and demand curves shown represent the simulation results for 90% service level for the adjusted (with depth variations removed) and original capacities.
FIG. 6.—Canal Capacities from Actual Irrigation Projects Compared to Rotation, Arranged and Demand Schedules, the Latter Two at 90% Service Levels

Capacities for 80 and 95% service levels are only slightly different from that for 90%. The Wellton Mohawk Irrigation and Drainage District appears to have been designed with an equation of the form \( Q = 30 + 0.01875A \) as a guide (C. W. Slocum, personal communication, Jan., 1980). When translated to the notation used here, with \( Q_d = 425 \text{ L/s (15 cu ft/sec)} \), \( W_b = 11.33 \text{ mm/day (0.446 in./day)} \), and \( A_T = 324 \text{ ha (800 acres)} \) this equation becomes \( Q_n = A_n + 2 \). This equation is shown in Fig. 6 along with some actual capacities for canals in the project. It appears that the equation was used only for the larger canals (say \( A_n > 1.5 \)) and probably rightfully so since the equation gave increasingly better service for very small \( A_n \). It appears that actual capacities for small service areas may have been a little low, or at least representing lower service capabilities than the larger canals. Capacity problems have arisen for canals with small service areas. Even so, this project operates very efficiently on an arranged schedule with flexibility in rate, frequency and duration.

From Fig. 4, the capacities required for a 90% service level are about 10–20% lower than those for a 95% service level and about 10–20% higher than those for an 80% service level for the demand simulation. From Fig. 5, the variation in adjusted demand capacity, as recommended for arranged capacities, from 80–95% is only about 10%. For many design situations, the differences are not significant. And judging from the performance of the two irrigation projects discussed here, a 90% service level is sufficient for canal capacity determination, particularly for the arranged systems.

Recommended Capacity Equations.—Many of the conditions represented by this simulation may be slightly unrealistic in that they do not represent an actual location. However, they may be viewed as a worst case situation since the variations in conditions were more than usual. On the other hand, farmer timing of irrigations would likely vary from that assumed here and more overlap could occur. Thus, for any given situation where a pure-demand system is desired, (that is, no limitations on rate, frequency and duration), the results presented here may be appropriate.

However, all future possibilities are generally not known at the time of design, such that more site specific simulations may not be justified. It is not known how demand patterns vary for conditions significantly different from those assumed for this simulation. It is not expected that they would vary greatly from those developed here. The major exception to this would be situations where early season irrigations require higher capacities than the period of peak ET use.

With these limitations in mind, the following curves shown in Fig. 7 are recommended for the determination of canal capacities for arranged and demand delivery schedules (based on 90% service levels). For the arranged schedules this curve can be approximated by

\[ Q_n = 1.6 A_n + 1 \quad \text{for} \quad A_n \geq 1 \]  \hspace{1cm} (13a)

\[ Q_n = A_n + 1.6 \quad \text{for} \quad A_n < 1 \]  \hspace{1cm} (13b)

Note that this is very similar in form to the W-M equation, at least for
A_n > 1 demand curve can be approximated by
Q_a = 4 A_n + 1 for \( A_n \leq 1 \) ...................... (14a)
Q_a = 1.5 A_n + 3.5 for \( A_n > 1 \) ...................... (14b)
which is also of a similar form.

Several other canal capacity relations are also shown in Fig. 7 for comparison. Note that the arranged schedule requires only a small increase in canal capacities over the rotation and continuous flow schedules. These differences may easily be overcome by increases in efficiency for most lateral and main canals. A demand system, however, requires considerably greater capacities being 2-3 times (for \( A_n > 2 \)) greater than that required for continuous flow. It is doubtful that the flexibility offered alone could improve efficiencies that much. Thus arranged systems can be justified by reductions in system costs and improved operations, while expanding canals to handle demand may not be easily justified. Farm reservoirs provide an attractive alternative when demand operation is required.

Also shown in Fig. 7 are the design curve for W-M and the results of Clement’s second formula (Clement II) for \( P_n = 0.10 \) and \( F = 1/16.3 \). Note that Clement II falls between the demand and arranged schedules. Clement II is only useful for arranged schedules at this service level from 0.2 < \( A_n < 2 \), with values 10-15% higher than the arranged curve for \( A_n > 2 \). The W-M design curve is relatively good for \( A_n > 2 \). For \( A_n < 2 \) it gives overly conservative results.

**CONCLUSIONS**

The modified CREAMS simulation model did a reasonably good job of developing demand patterns for surface irrigation. These demand patterns would likely vary for different crop mixes, climatic areas and seasons. However, the resulting canal capacity relations developed should still be reasonable for slightly different conditions.

Clement's two equations for canal capacity are clearly not appropriate for demand under surface irrigation. As stated by Clement, the development of these equations is appropriate only for \( A_n > 5 \). The results are particularly bad for \( A_n < 1 \) since \( Q_n \) is allowed to go below 1. These results fall closer to the arranged capacities developed.

The capacity relationships developed for arranged delivery systems appear to be reasonable. However, the exact type of restrictions on an arranged system may cause differences in required capabilities. This point has not been adequately studied. In some sense, these arranged capacities are speculative.

The approximate equations developed for demand and arranged canal capacities at a 90% service level are simple to use. The selection of this service level has a minor effect on arranged capacities, but can have a significant effect on demand capacities. Also, the wide range of conditions used in simulation may have produced demand capacities higher than necessary. The arranged capacities should not be affected.

Finally, these relations do not consider the additional congestion caused by restricting capacity. At very high service levels (e.g., 99%) is not a significant problem. The service level at which this produces significant impact is not known.

**APPENDIX—REFERENCES**