EVALUATION OF SURGE FLOW

FURROW IRRIGATION IN THE

JORDAN VALLEY

BY

MUHIB A. AL-AWWAD

The examining Committee Considers this thesis Satisfactary and acceptable for the award of the Degree of Master of Science in Soils and Irrigation.

Approved:

Muhammad Shatanawi : Assistant Professor of Irrigation Engineering. Advisor.

Ibrahim Ghawi : Assistant Professor of Soil Physics. Committee Member.

Othman Judah : Assistant Professor of Irrigation Engineering. Committee Member.

Theib Y. Oweis : Assistant Professor of Irrigation Engineering. Committee Member.

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Muhib A. Al-Awwad

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Surface irrigation methods are generally inefficient; high surface runoff and deep percolation losses are cited as their main disadvantages. Furthermore, the differences in opportunity times along the field length causes nonuniform distribution of water. Therefore, attention is focused on the means of cutting down advance time to reduce the difference in opportunity time between the two ends of the field. Faster completion of the advance phase may be achieved by surge flow irrigation (1,2,7,22,28,30) .

Surge flow may be defined as, the "intermittent application of irrigation water to furrows or border strips creating a series of constant or variable time spans "(2). Previous research indicates that surge flow technique may improve surface irrigation efficiency and distribution uniformity, thus water loss by runoff and deep percolation may be significantly reduced (1,2,7,22).

The major advantages of the surge flow technique might help in removing many of the trial and error managment methods now commonly employed by the irrigator, and shows great promise for design of irrigation systems (7). In addition, fields of long runs may be irrigated by surge flow where in continuous flow shorter distances are usually used.

The contribution of this work falls in two-folds: first, studying the performance of surge flow furrow irrigation under the experiment conditions ; second, using the obtained data in further analysis of this technique (distribution uniformity and application efficiency).

CHAPTER II

REVIEW OF LITERATURE

Surge flow irrigation was first suggested by Stringham and Keller (28) as an improvement of furrow irrigation. The surge flow phenomena was actually discovered while conducted reasearch on the automation of furrow irrigation. The authors were trying to achieve a cutback process by completely closing off automatic valves rather than partially for conviences. However, the surge flow process in surface irrigation may have been practiced in a random simple way by farmers long before it came under research focus (22). The research on furrow irrigation cutback systems led to the present surge flow practice.

Bishop, et al. (2) defined surge flow as, " the intermittent application of irrigation water to furrows or border strips... creating a series of on and off modes of constant or variable time spans",and the cycle time as,"the period required for a complete on/off cycle;i.e.,the time between the beginning on one surge to the beginning of the next. " The on-time is,"the time during which water is applied,"while the off-time is,"the time during which water is cutoff." The same authors defined the cycle ratio as, "the ratio of on-time to cycle time," i.e.,continuous flow has a cycle ratio equal to one.

Stringham and Keller (28) studied three banks of four furrows each. They used an inflow of 0.82 lps and furrows of 201 m long in comparing surging with continuous flow. They noted that advance time for surged furrows was less than that for the continuously irrigated furrows, although smaller stream sizes (50%, and 67 %) of that used for continuous flow were used. They also indicated that surge flow had an effect on the furrow intake rate. They stated that " if subsequent tests verified this phenomenon, the implications would be extremely interesting in terms of distribution uniformity along the furrows and runoff rates ".

Bishop, et al. (2) carried out a field study to test the characteristics of surge flow irrigation in furrows with particular emphasis on the advance phase. They used instantaneous furrow streams of 0.63 , 1.26, and 1.89 lps with cycle ratios of one, one half, and one third, respectively, resulting in an equal quantity of water being applied to each furrow over a given period of time. The cycle time for each test was 10 minutes. Bishop, et al. (1,2) reported a field study using surge flow furrow streams of 1.26 lps with cycle times of 2,5,10 and 20 minutes; in all cases the cycle ratio was one half, making the time averaged flow rate 0.63 lps and equal to that continuous flow furrows irrigated at the same time for comparison. The above two studies were carried out at Utah

State University, in which.the soil was classified as a silt loam planted with corn. The length of the furrow was 183 m with an average slope of 1.46%. The results of these studies showed that continuous flow treatments on a noncompacted furrow required twice to four times the time needed by the surge flow treatments to complete the advance phase in the first irrigation. It was also observed that the differences was less significant between advance under surge and continuous flow for the next irrigation.

Bishop, et al. (1,2), in analyzing previous results,indicated that the variability effects on advance were reduced to nonsignificant point under surge flow conditions. They also indicated that advance under surge flow is significantly higher than under continuous flow.

Coolidge, et al. (7) conducted two experiments for studying surge flow on-time effects in a silt loam soil. First,they measured total time required to advance 100 m using 5,10, and 20 minutes on-times with a cycle ratio of 0.5, and continuous flow. Second, the same cycle on-times were used with cycle ratios of 0.25, 0.50, and 0.75, respectively. Flow rate was 0.3 lps. Also, they used an approximation method to calculate the time required to advance 100 m . In analyzing the results of the above two experiments, the authors concluded that the 10 and 20 minutes on-times advanced 100 m using only 38% and 56% of the volume of water used by continuous flow to advance the same distance. A total elapsed time of 83, and 108 minutes were needed for surge and continuous flow treatments, respectively. Surging with 5 minutes on-time differed little from continuous flow, they theorized that the reason is that the on-time was insufficient to overcome dead storage and infiltration requirements. The same authors (7) stated that the standard deviation for surge flow treatments ranged from 14% - 47% from the values of continuous treatments, which showed another major advantage of the surge flow method.

The same authors (7) reported studies on water distribution and uniformity. An experiment was conducted using a gravimetric soil moisture samples collected from three stations before and after each of the two separate pulsed irrigation. The results showed that, surge, flow improved application uniformities significantly, and the applied depths at the furrow head were generally higher than elesewhere along the furrow as one might expect.

A team from Utah State University (22) conducted field experiments for studying surge flow phenomenon. The experiments were conducted in the summer of 1981 at three locations in Utah and Idaho. The first was near Flowell, Utah, on a 360 m furrowed corn field in a sandy loam soil; the second was near Kimberly, Idaho, on a 360 m furrowed bean field in a silty caly loam soil ; and the third was near Logan, Utah, on a 150 m fallow field in a silty clay soil. The flow rates used in these tests ranged from 0.8 to 2.0 lps. A fixed cycle ratio of 0.5 and variable cycle times were used . The furrows used were compacted and noncompacted ones with slopes ranging from 0.5 to 0.8 % .

Walker, et al. (30) analyzed the above three experiments and concluded that the results of Logan and Kimberly tests confirmed the conclusions obtained by Bishop, et al. (2) and Coolidge, et al. (7) which were discussed earlier in this chapter. However, the results of Flowell location were significantly different. They reported that, while 2.0 lps continuous flow failed to irrigate more than 80 % of noncompacted furrow length in 8 hours, a 40 minutes surging wetted the entire furrow length in 3 hours of application time ; an almost three-fold difference in terms of average depth of application. In compacted furrows, advance was completed in just less than 8 hours with continuous flow and just over 2 hours with a surge flow regime.

They related the differences between Flowell and Kimberly and Logan to soil differences and the design and operational criteria used at the three locations. They stated that "better results with surge flow in lighter soils could provide a great potential for substantial improvement in surface irrigation efficiencies on these problem soils".

The distribution uniformites and application efficiencies improved significantly using surge flow. Walker, et al. (30) showed that the low-quarter distribution uniformity, defined as the average depth infiltrated into the least watered quarter of the field divided by the average depth infiltrated into the entire field, ranged from 77 % for the 480 and 30 minutes cycles to 81 % for the 120 minutes cycle at Flowell location. They also stated that, the distribution uniformity for the four continuous flow treatments ranged from 88 % for the six-hour application to 72% for the three-hour application . They also reported that, the distribution uniformity acheived by irrigating the field in half length is approximately equal to the surge flow treatment on full length furrows, even though the advance phase had been completed for a shorter period of time for the surge flow simulations.

Depending on Flowell location results, the same authconcluded that infiltration depends on an averaged water application rate regardless of the mode of water application (continuous or pulsed).

Bishop, et al. (2) theorized that surface sealing may be responsible for the phenomenon. As first pulse lubricated particles in the surface soil may be reoriented horizontally and in a plate fashion that would greatly reduce infiltration in the wetted section of the furrow. They also stated that, the development of tension forces in the soil following surface drainage may consolidate the surface layer and cause the infiltation to change.

Bishop, et al. (2) concluded that the effects of surge flow on the soil hydraulic characteristics were extreme during the first irrigation. The same authors (2) indicated that the effects of surge flow on the soil infiltration rate are probably the most important aspect of this new surface irrigation technology. Then, they theorized that surge flow accelerates the formation of soil surface seal by dispersed fine particles which was lubricated by water and compacted by tension forces which buildup in the soil as water drains continues.

Coolidge, et al. (7) theorized that surge flow effects were a relatively rapid process. The effect on intake rates must be derived from draining the water from the furrows between surges, which give a possibility that the effect occurs during the first off time after the wetting of a section of furrow, and that the process continues on subsequent pulses without measurable change and with increasing conductivity of the layer below the seal .

Furrow Infiltration

Infiltration is an important factor in any irrigation system. In most of the cases water enters the soil vertically, so that infiltration is considered one-dimensional flow problem (8,14,27). Furrow infilitration continues to be a difficult task, since water penetrates the soil vertically and horizontally(11). It is still difficult to know the vertical and horizontal infiltration in the furrow due to its geometry which presents the problem of a variable wetted surface area (11,12).

Walker, et al.(31) carried out the first field test for investigation of infiltration process under surge flow conditions. They used a flowing infiltrometer in which infiltration was recorded in a short section of the furrow by the difference between inflow and outflow over a certain periods.

They used the Kostiakov- Lewis intake function to fit the data obtained. They reported that cycled water applications reduced infiltration in furrows. They concluded that a mechanical dispersion of very small clay and silt particles over the wetted surface may create a surface seal which consolidated during the draining period.

Furrow infiltration rate can be represented in many functional forms. The most common function which has been used to characterize infiltration rate in furrows is the Kostiakov equation (25,34)

$$z = k \quad t^a \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

in which z= the infiltrated volume per unit length of furrow; t= the infiltration opportunity time, and k and a = empirical constants.

The above Kostiakov equation was modified to account for the basic infiltration rate, which then was called the modified Kostiakov-Lewis equation (32)

$$z = k \quad t^a + ft \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

in which f = another empirical constant represents the basic infiltration rate.

The numerical values of the above empirical constants depend on the method used to determine them. Direct determi-

CHAPTER III

METHODOLOGY

The study was carried out at the University of Jordan Research Station (site A) ; and at the Ministry of Agriculture Experiment Station at Deir Alla (site B). The two sites are in the Jordan Valley.

Furrows of 80 m long and 1.5 m spacing were prepared on 1.36% uniformly graded land at site A. The furrows were considered compacted furrows due to grading process. They were generally of parabolic shape with an average depth of 20 cm, 70-cm circumstance, 30-cm middle width, and average topwidth of 60 cm. At site B, two sets of furrows, of 220 m long and 1.8 m spacing were prepared with an average slope of about 0.01%. The furrows were considered noncompacted. These furrows were generally of parabolic shape with an average depth of 27 cm, 73-cm circumstance, 35-cm middle width, and average topwidth of 67 cm.

Prior to running the test, 5-meter stations at site A, and 10-meter at site B were established in order to detect advance and recession times. Wood stakes were then fixed at those stations . When water was applied , the advance and recession times required to reach each station were recorded using stopwatches. Direct volume measurement was used to establish a

Table 1.- Different Runs Used For

Studying Surge Flow

At Site A.

Furrow No.	Cycle Time (minutes)	Cycle Ratio	Discharge (lps)
1	10	0.5	0.5
2	16	0.5	0.5
3	20	0.5	1.0
4	30	0.5	0.5
5	1560*	1.0*	1.17*
6	40	0.5	0.5
7	40*	0.5*	1.17*
8	150	1.0	0.5
9	60	0.5	0.5
10	10	0.5	1.25
11	50	0.1	2.5
12	50	0.2	1.25
13	50	0.3	0.83
14	50	0.4	0.625
15	50	0.5	0.5
16	50	0.6	0.42
17	50	0.7	0.356
18	50	0.8	0.313
19	50	0.9	0.275
20	50	1.0	0.25

* Infiltration Function Measurements.

Table 2. - Different Runs Used For Studying Surge Flow At Site B.

Furrow No.	Cycle Time (minutes)	Cycle Ratio	Discharge (lps)
1	50	0.6	2.0
2	50	0.4	2.0
3	60	0.5	1.5
4	480	1.0	1.0
5	430	1.0	1.5
6	60	0.5	1.0
7	120	0.5	1.5
8	90	0.5	1.0
9	120	0.5	1.0
10	90	0.5	1.5
11	120	0.5	2.0
12	360	1.0	2.5*
13	60	0.5	2.0
14	360	1.0	2.0
15	90	0.5	2.0
16	50	0.5	2.0
17	40	0.5	2.0
18	60	0.5	2.5*
19	90	0.5	2.5*
20	120	0.5	1.5
21	IFM	1.0	2.0
22	IFM	0.5	1.5
23	IFM	0.5	2.0
24	IFM	0.5	2.5*

IFM = Infiltration Rate Measurement .

* Maximum Nonerosive Furrow Stream Size (13).

outflow measurements were made using four furrows in which the flow rates delivered to the heads of the furrows were 2.0, 1.5, 2.0 and 2.5 lps. The whole furrow length (220 m) of each furrow was used as one unit for measuring infiltration. The flow rates were determined and measured directly using calibrated bucket and stopwatch .

Infiltration under continuous flow was measured by continuous application of water; while infiltration under surge flow was measured by continuous application of water after application of surge flow treatment. At site A, the surge flow treatment has 40 minutes cycle time and 0.5 cycle ratio. At site B, 90 minutes cycle time with 0.5 cycle ratio were used. The values obtained from these treatments were considered average values and to be used in all surge treatments.

Three different time spans were selected from each infiltration rate test run and put into the modified Kostiakov-Lewis equation, ending up with three independent equations. The empirical constants of the modified Kostiakov - Lewis equation were then found by sloving those equations simulatnously.

CHAPTER IV

RESULTS AND DISCUSSION

Infiltration Functions

The infiltration function of the soil is a very important factor required for analysis and design of furrow irrigation systems. Determining the infiltration function in furrows is a difficult task since water is infiltrating vertically and horizontally into furrow sides. Among different infiltration functions, the modified Kostiakov - Lewis equation was selected to be used for further analysis and evaluation of surge flow. This is because it is flexible , its empirical constants could be determind by many techniques, and easily to be solved numerically (12).

The general form of the modified Kostiakov - Lewis infiltration equation as defined in chapter II is

$$z = k\,t^{a} + ft \quad \text{..................(2)}$$

in which z = the infiltrated volume per unit length of the furrow; t = the infiltration opportunity time; and k , a , and f = empirical constants. The subscripts c , and s shall denote continuous and surge flow conditions, respectively .

Introducing three different time spans from three different furrows using the procedure described in chapter III furrow required twice to four times the time needed by the surge flow runs to complete the first irrigation advance . Walker, et al. (30) reported that, while 2.0 lps continuous flow failed to irrigate more than 80% of the length of non-compacted furrow in 8 hours, 240 minutes surging wetted the entire furrow length in 3 hours of application time; an almost three- fold difference in terms of average depth of application .

Field comparisons of surged and continuous flow regimes are shown in figures 1 through 13. Successive advance and recession trajectories for 1.0 lps with a cycle ratio of 0.5 and cycle times of 60,90 and 120 minutes, are shown in figures 1,2, and 3, respectively. Continuous flow advance trajectories for the same discharge are superimposed on the same figures. In these runs, 1.0 lps flow rate applied in a continuous manner needed 7.48 hours to complete advance 220 m furrow . On the other hand surge flow runs of the same flow rate required 3.0, 3.0, and 3.82 hours to advance the same furrow length under 60, 90 and 120 minutes cycle times respectively, The above comparison between surge and continuous flow regimes indicates that, surge flow runs advanced the entire furrow lenth faster,

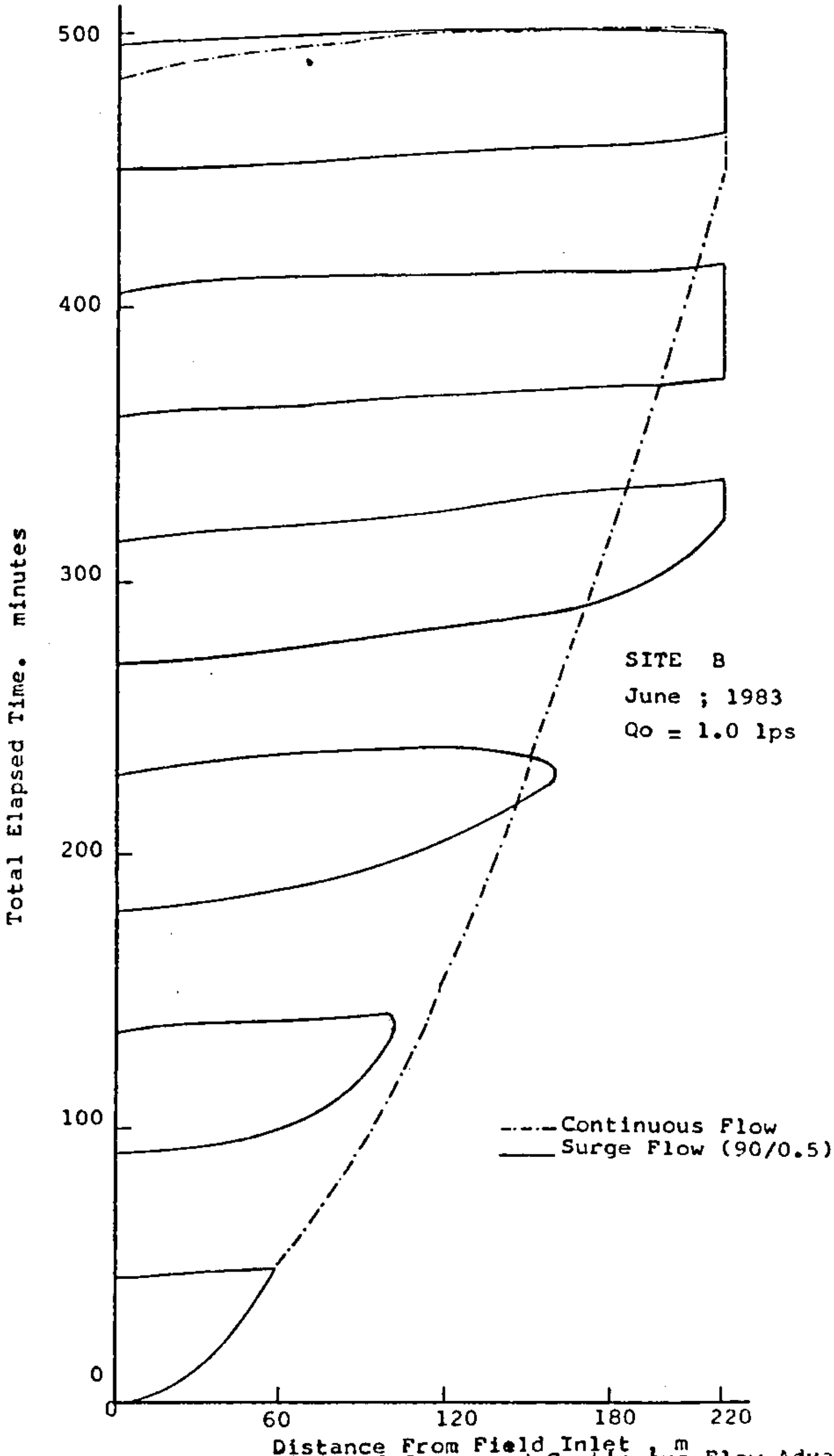

FIG.2.-Comparison of Surge and Continuous Flow Advance and Recession Rates in a Clay-Loam Furrow.

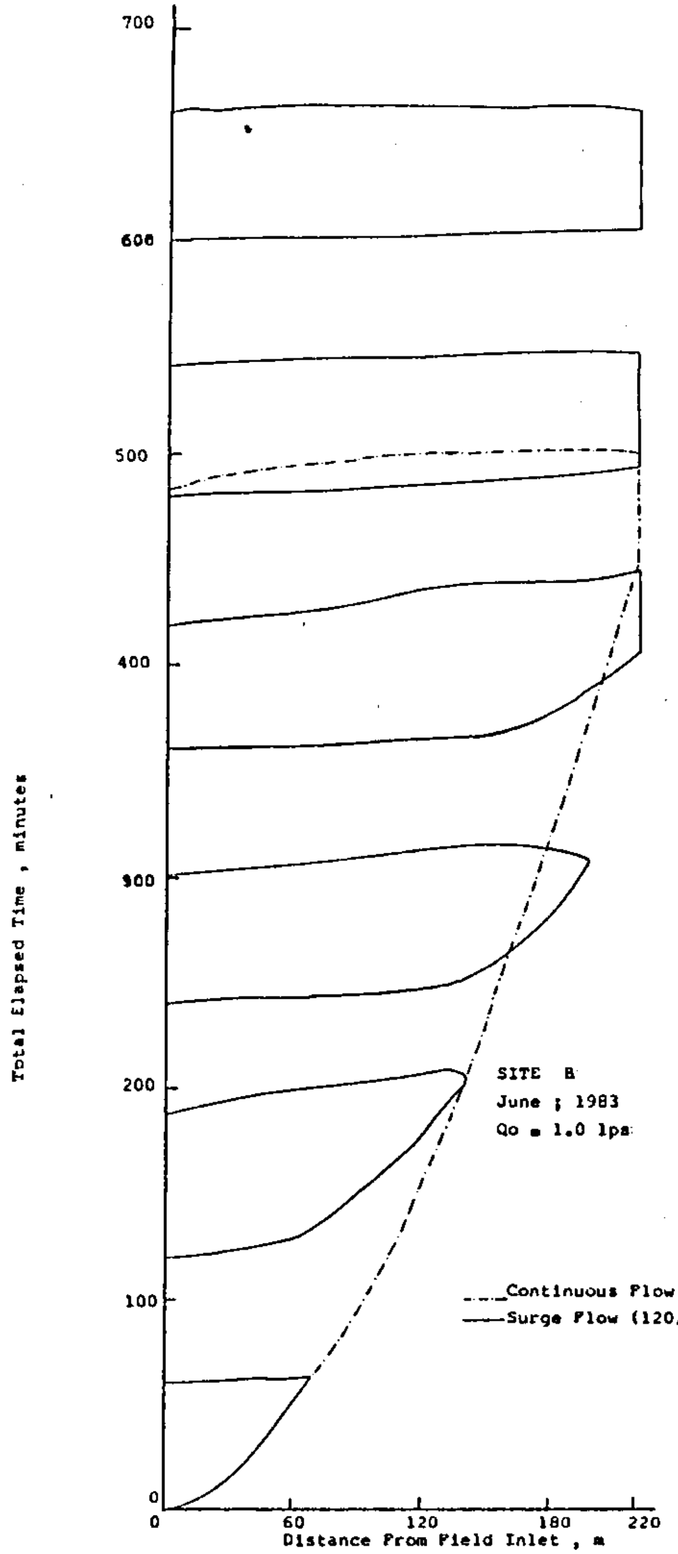

FIG.3.-Comparison of Surge and Continuous Flow Advance and Recession Rates in a Clay-Loam Furrow.

and needed only 0.40, 0.40, and 0.51 of the continuous application time and volume the above ratios. Less than half of the water was consumed by surge flow, which are very close to the results reported by Coolidge, et al. (7) and Walker, et al. (30). Coolidge, et al. (7) concluded that surge flow runs advance 100m using only 38% and 56% of the volume of water used by continuous flow to advance the same distance. While Walker, et al. (30) concluded that the surge flow system could at least save half the water being used if operated in conjuction with an irrigation scheduling program.

Successive advance recession trajectories for 1.5 lps (other parameters are the same as before) are shown in figures 4, 5, and 6. Total application times required to advance to the end of the field are 3.0, 2.72, and 2.87 hours which corresponds to 6, 4 and 3 surges of 60,90 and 120 minutes cycle times, respectively. Continuous flow required 6.58 hours to advance to the end of the field. Comparison between application times for surge flow runs and continuous flow indicates that only 0.46, 0.34, and 0.44 of the continuous flow time and volume were needed for surge flow.

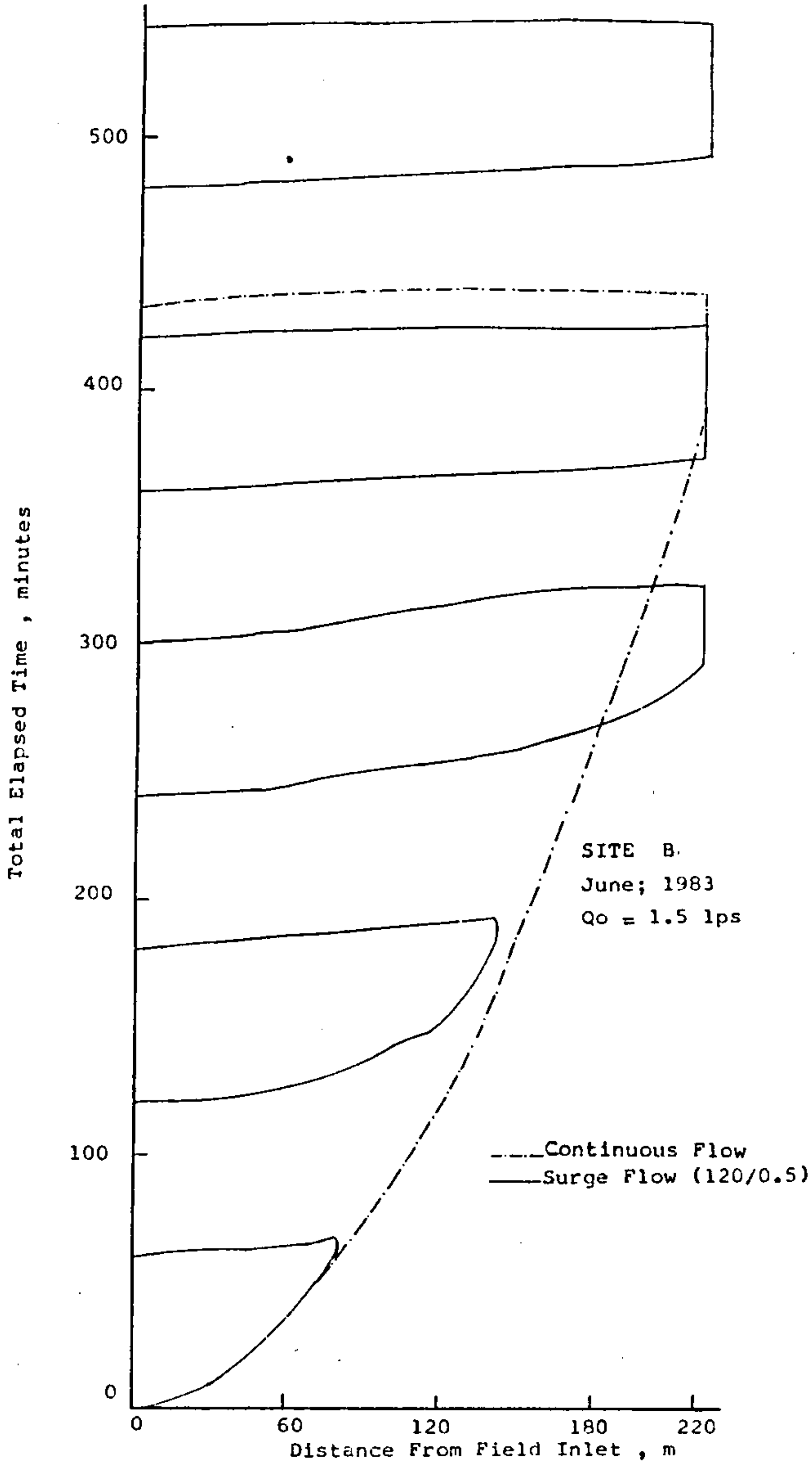

FIG.6.- Comparison of Surge and Continuous Flow Advance and Recession Rates in a Clay-Loam Furrow.

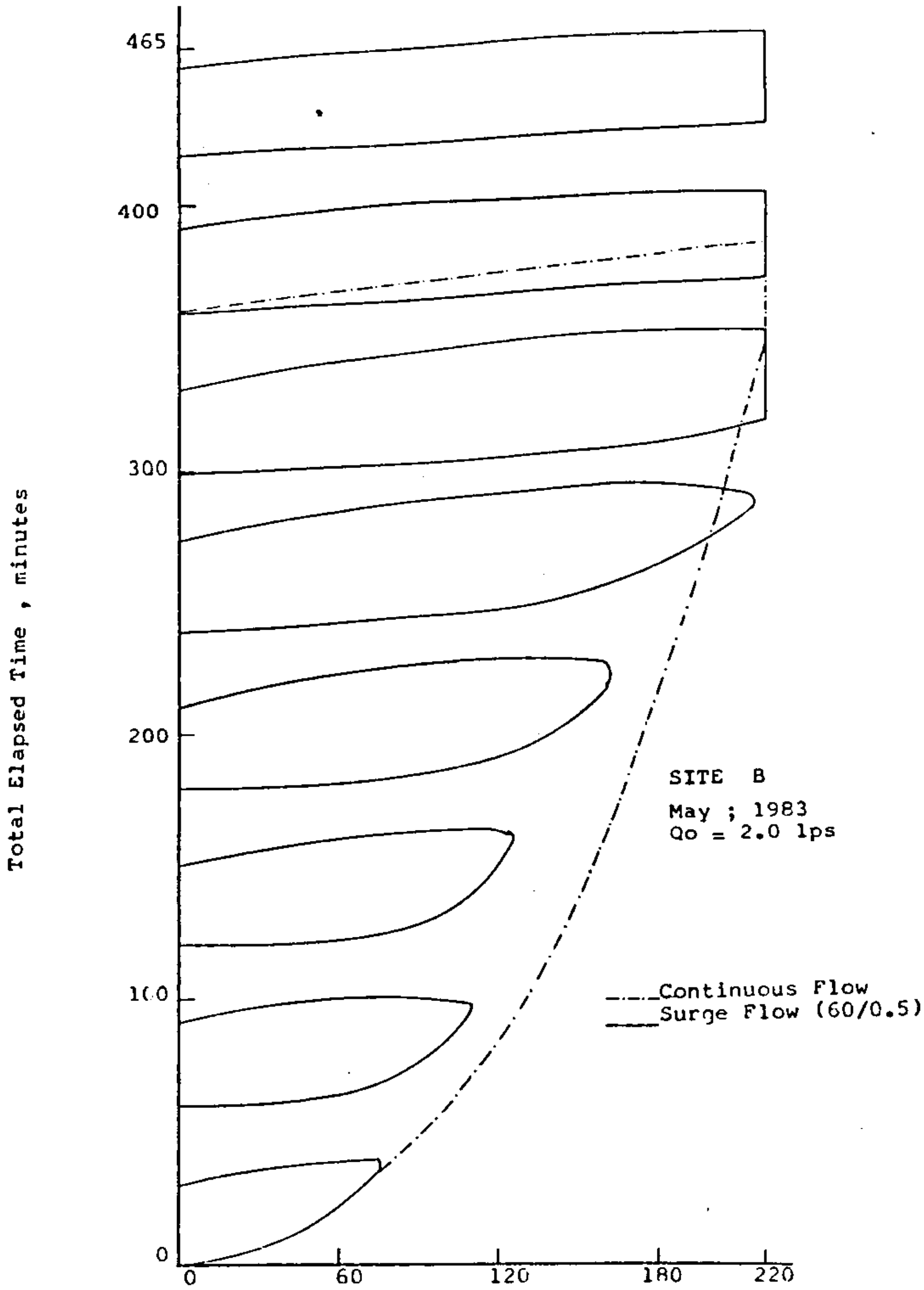

FIG.7.-Comparison of Surge and Continuous Flow Advance and Recession Rates in a Clay-Loam Furrow.

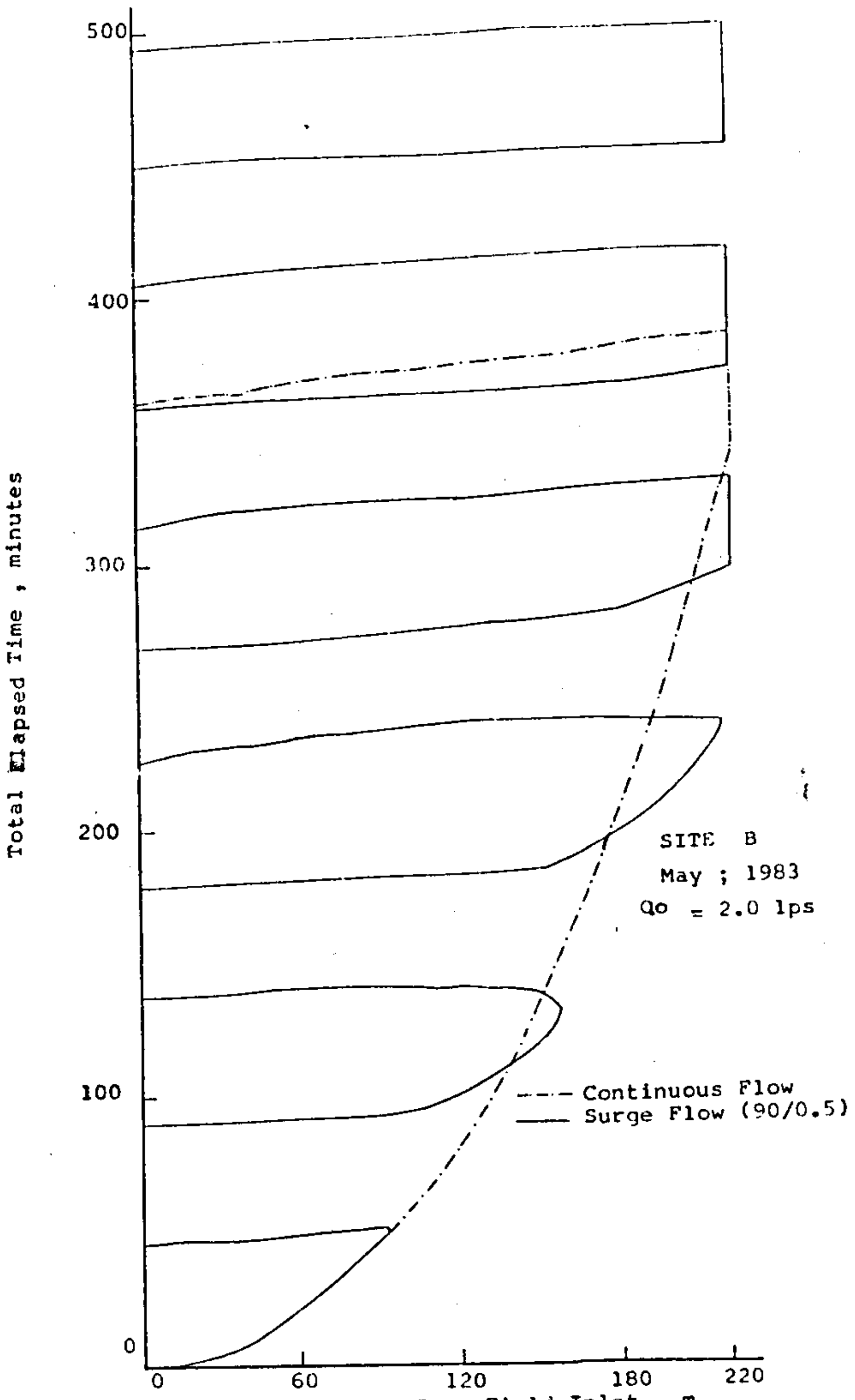

FIG.8.-Comparison of Surge and Continuous Flow Advance and Recession Rates in a Clay-Loam Furrow.

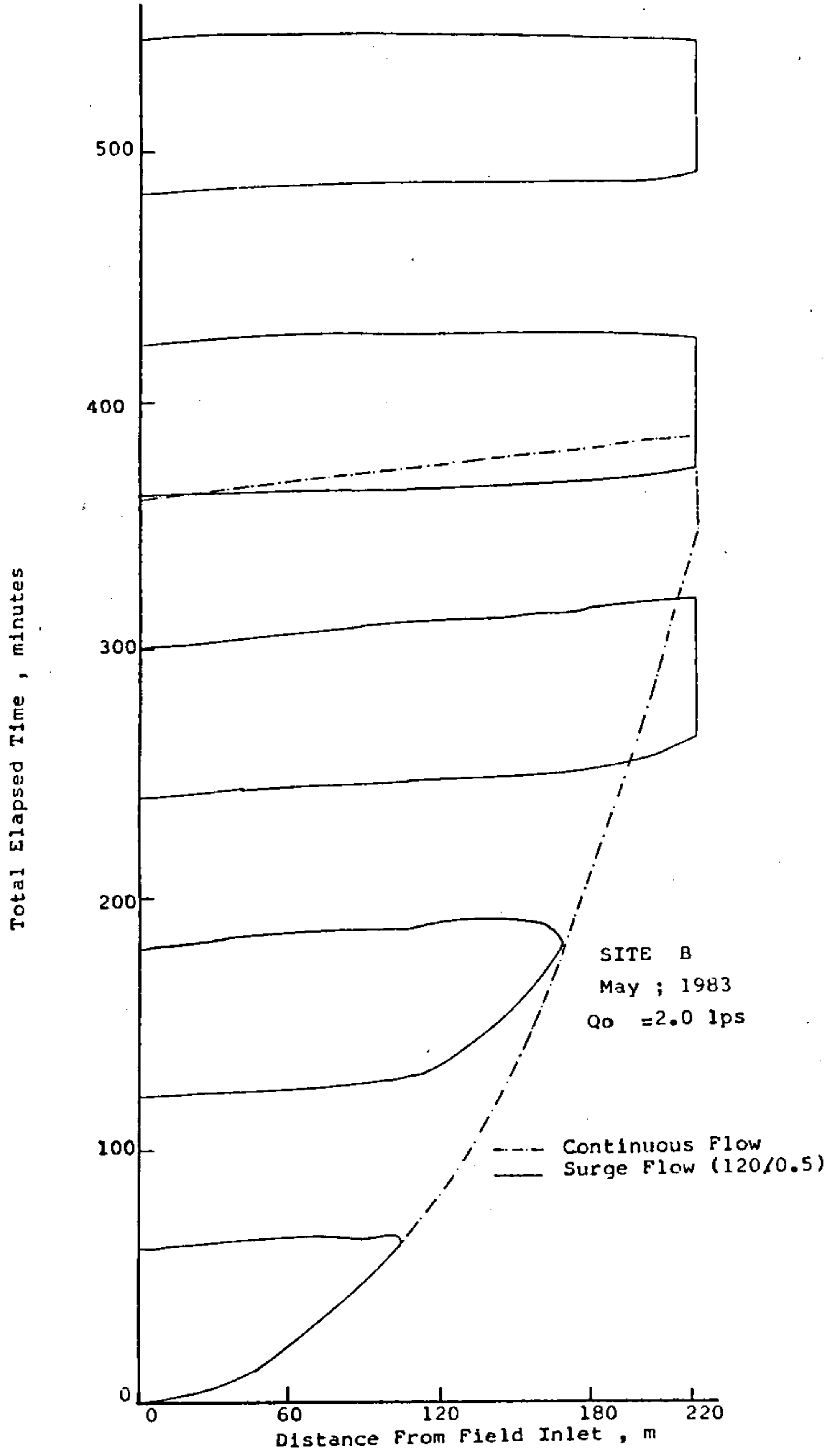

FIG.9.- Comparison of Surge and Continuous Flow Advace and Recession Rates in a Clay-Loam Furrow.

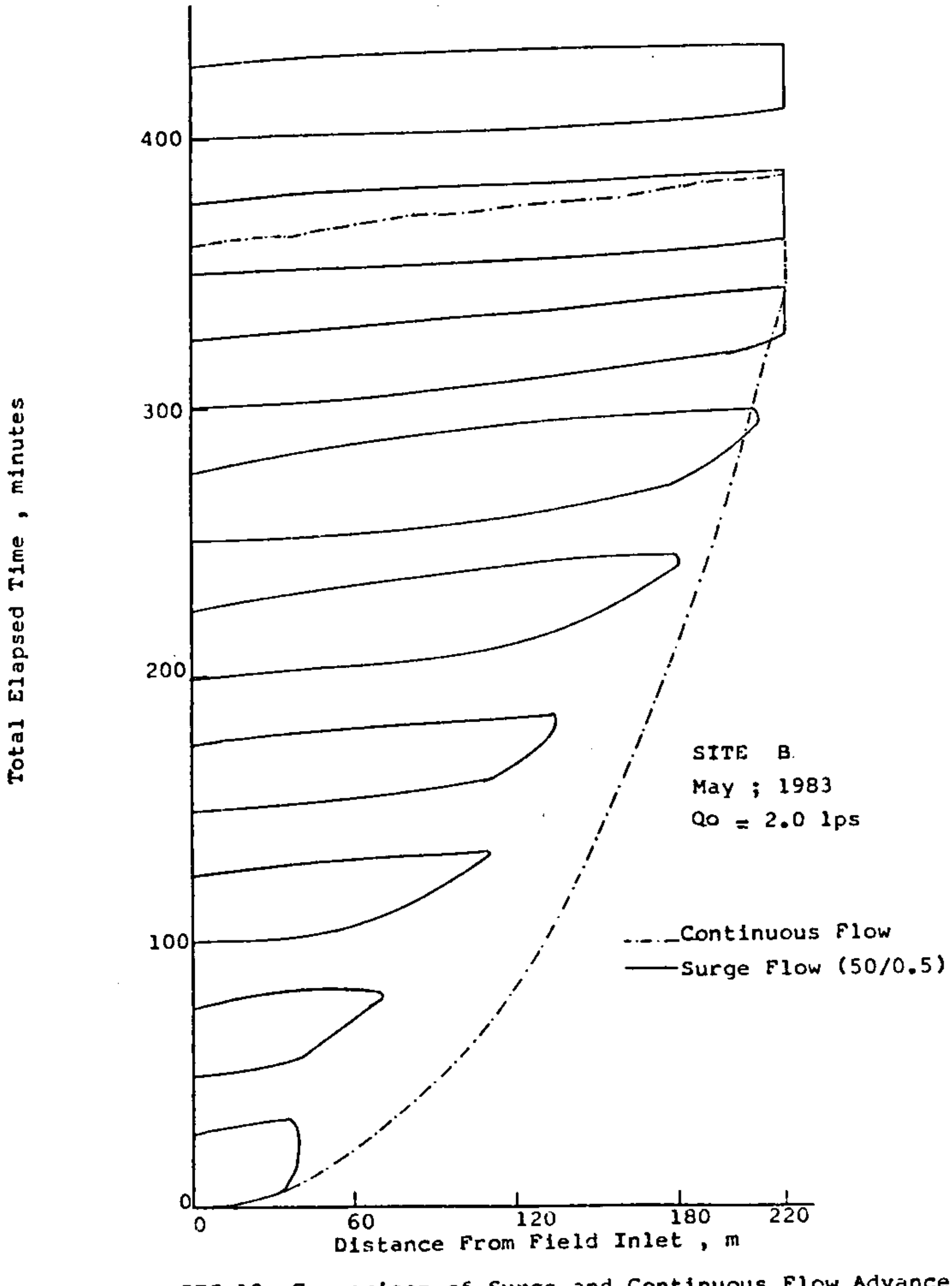

FIG.10- Comparison of Surge and Continuous Flow Advance and Recession Rates in a Clay-Loam Furrow.

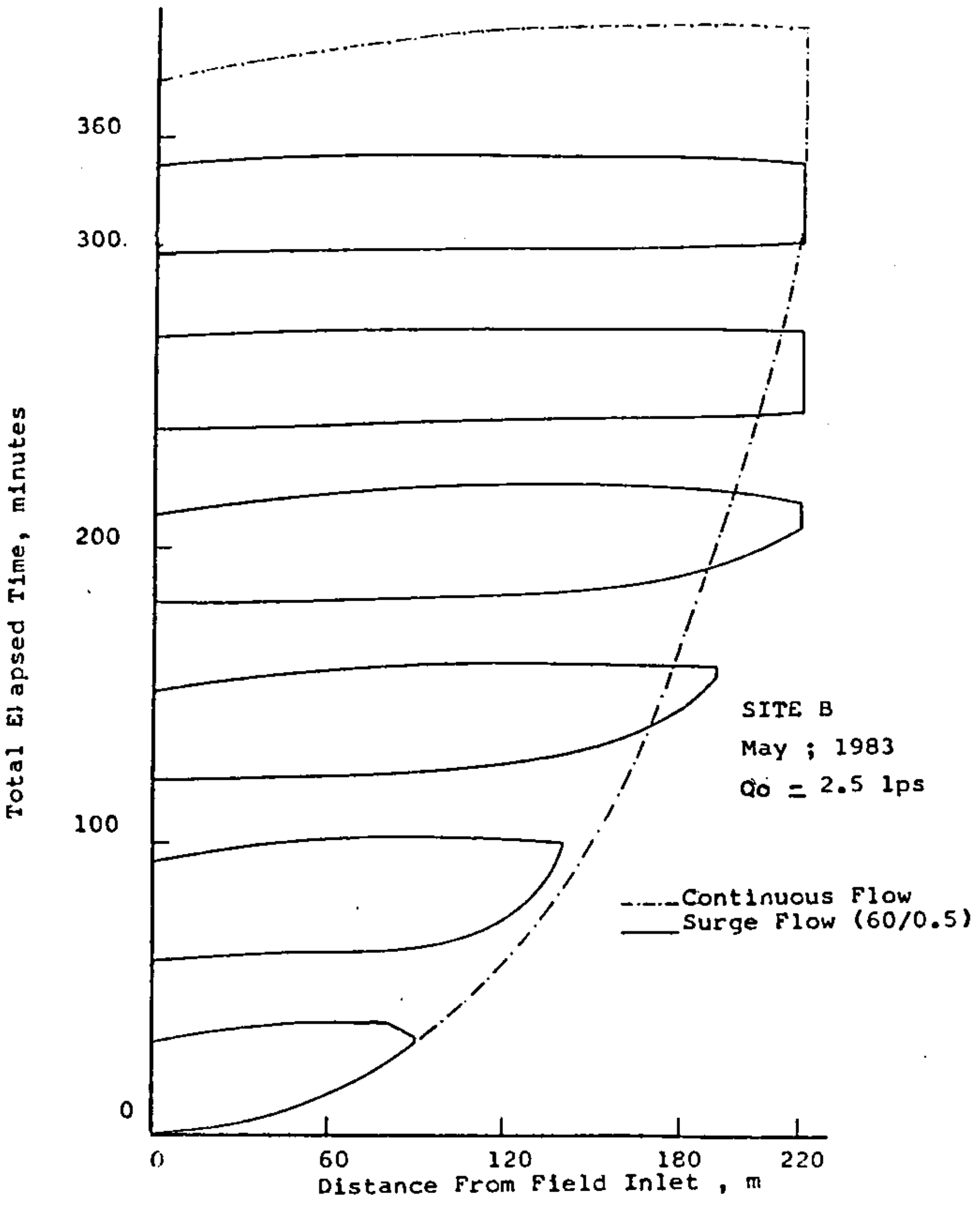

FIG.11.-Comparison of Surge and Continuous Flow Advance and Recession Rates in a Clay-loam Furrow.

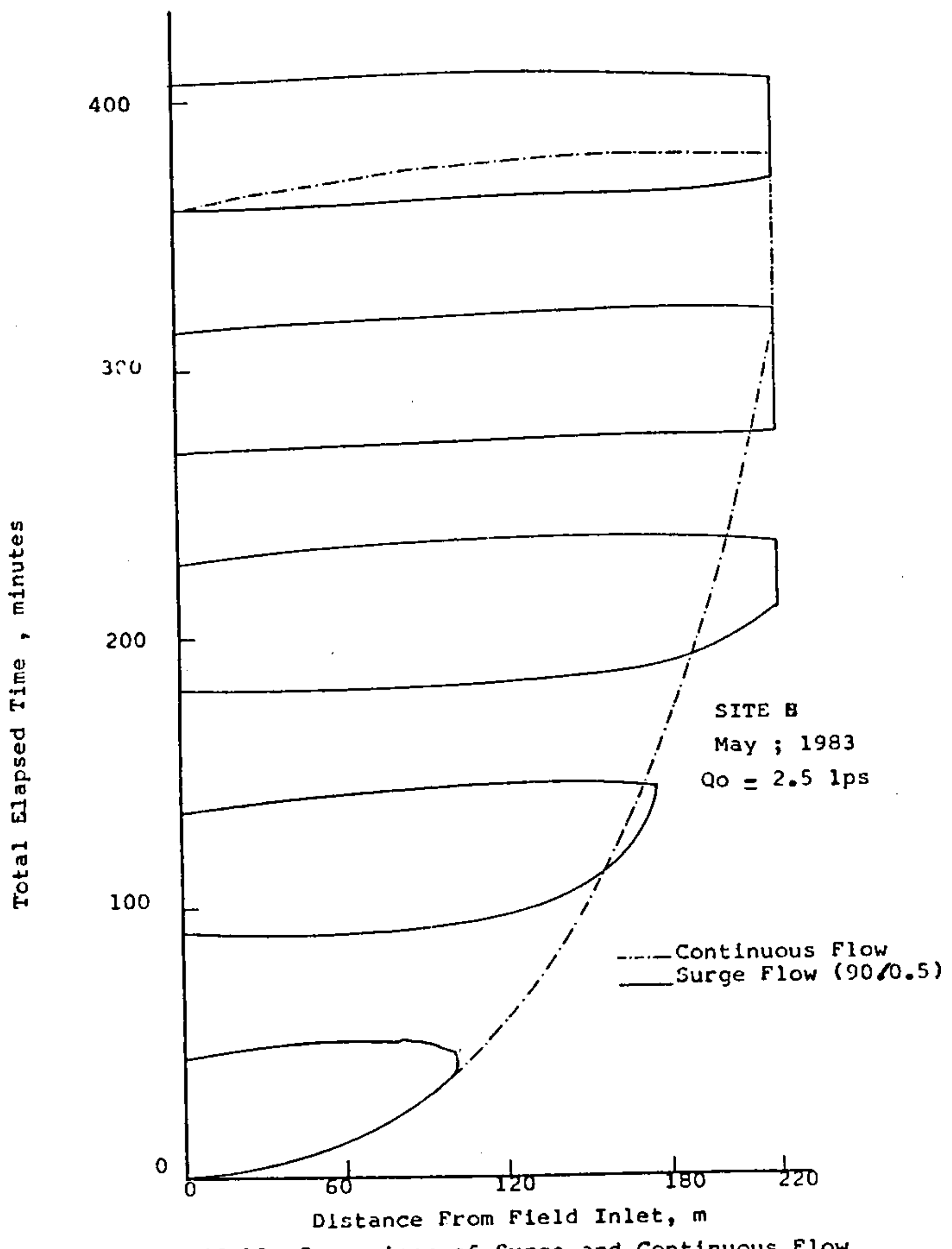

FIG.12.-Comparison of Surge and Continuous Flow Advace and Recession Rates in a Clay-Loam Furrow.

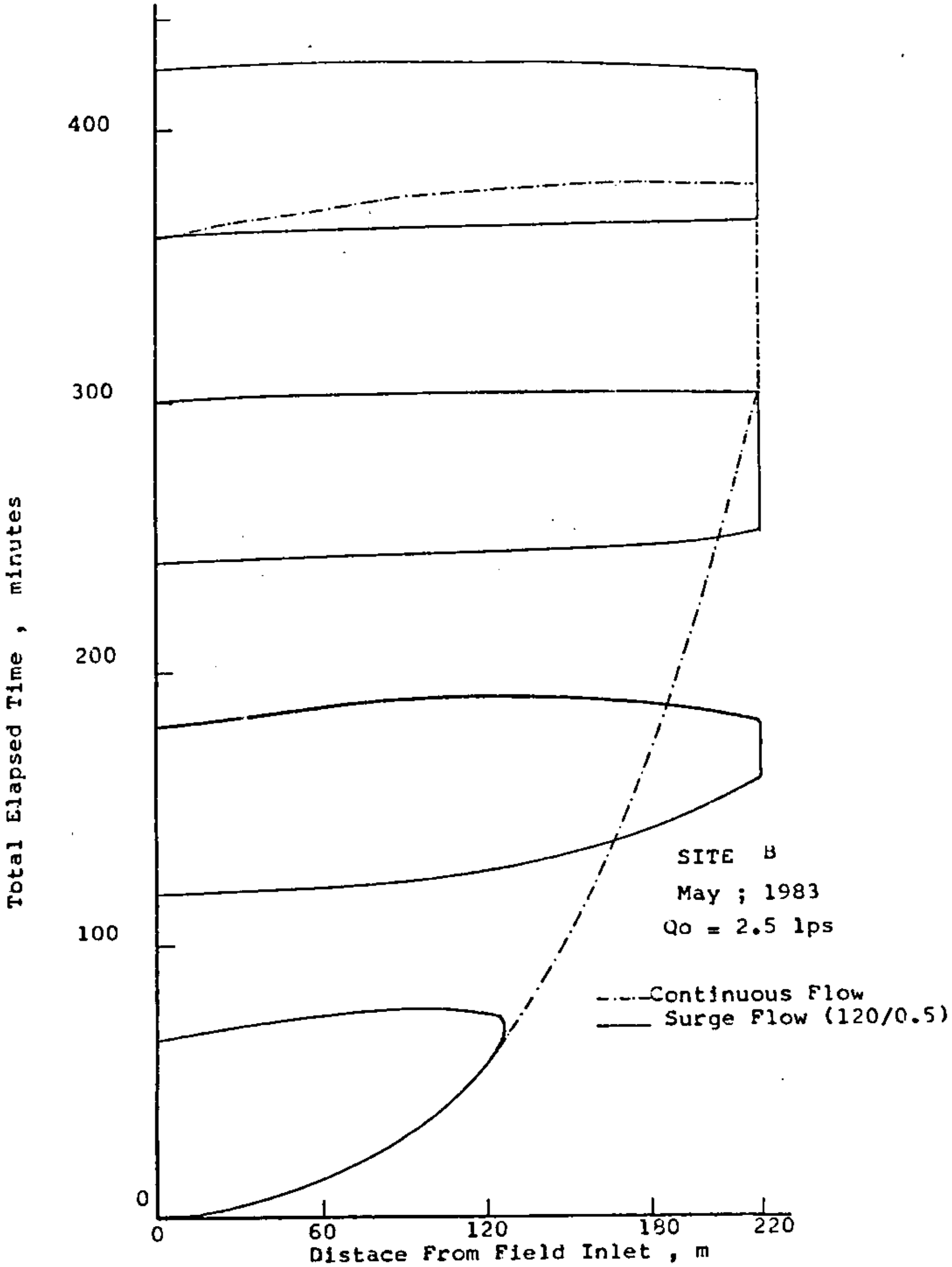

FIG.13.-Comparison of Surge and Continous Flow Advance and Recession Rates in a Clay-Loam Furrow.

Surge flow runs of 2.0 and 2.5 lps which are presented in fiqures 7 through 13 show the same general trend. Comparison of 2.5 lps surge and continuous flow volumes showed little difference. Surge flow runs of 60, 90, and 120 minutes cycle times used only 0.38, 0.39, and 0.3 of the volume used by continuous flow, respectively. Only about one-third of water required for continuous flow was needed by surge flow to advance the same length of the furrow.

Comparison of surge and continuous flow recessions (fiqures 1 through 13) indicates that there is no difference between surge and continuous flow in the first surges. While indicates that surge flow recessions were faster than continuous flow recessions in the last surges (especially the last three surges). This due to smaller volumes of water applied in surge flow runs, so that they will recceed faster.

Runs at site A did not show significant difference between continuous and surge flow advance recession trajectories. This is due to the fact that the furrow length was only 80 meters and the flow rate used was large enough to advance to the end of the furrow in one surge.

Surface Runoff

Table 3 shows the total surface runoff for different runs at site A. The same volume of water is being applied in each run. As a general trend, the total surface runoff under surge flow was larger than that under companion continuous flow. This might be due to the lower infiltration rate under surge flow than that under continuous flow. This is clear from low empirical values of infiltration function constants under surge flow. Surge flow effects appeared more promenant under lengthy fields as reported in the litreature (2,7,22,30,31) in addition to the data obtained and shown before.

Considering surface runoff for each surge, which is shown in table 4, indicats that surface runoff due to the first surge after completing the advance is small compared to the second. While surface runoff due to the third surge is little different than that due to the second surge. After the third surge negligible surface runoff difference between subsequent surges was noticed . The above situation may be due to the increase in soil water content as water was applied until the third surge where a saturation conditions were reached . This lead to a constant infiltration rate. When water applied

Table 3. - Total Surface Runoff
For Different Runs At
Site A.

Qo (lps)	Run*	Volume Applied(VA)m^3	Surface Runoff(SR)in m^3	$\frac{SR}{VA}$ x 100
0.5	150/1.0	4.50	2.06	45.78
0.5	10/0.5	2.25	1.18	52.44
0.5	16/0.5	2.40	1.82	75.83
0.5	30/0.5	2.25	1.40	62.22
0.5	40/0.5	2.40	1.87	77.92
0.5	50/0.5	2.25	1.69	75.11
0.5	60/0.5	2.70	1.47	54.44
1.0	150/1.0	9.00	6.02	66.89
1.0	20/0.5	4.80	3.80	79.17
1.25	10/0.5	2.25	1.38	61.33
2.5	50/0.1	2.25	1.44	64.00
1.25	50/0.2	2.25	1.17	52.00
0.83	50/0.3	2.25	0.92	40.89
0.625	50/0.4	2.25	1.15	51.11
0.5	50/0.5	2.25	1.65	73.33
0.42	50/0.6	2.25	1.37	60.89
0.356	50/0.7	2.25	0.84	37.33
0.313	50/0.8	2.25	0.95	42.22
0.275	50/0.9	2.25	1.05	46.67
0.25	150/1.0	2.25	0.22	09.78

* CYCLE TIME/ CYCLE RATIO

Run*	Qo (lps)	VA (m^3)	1st Surge SR (m^3)	1st Surge VI (m^3)	2nd Surge SR (m^3)	2nd Surge VI (m^3)	3rd Surge SR (m^3)	3rd Surge VI (m^3)	4th Surge SR (m^3)	4th Surge VI (m^3)	5th Surge SR (m^3)	5th Surge VI (m^3)	6th Surge SR (m^3)	6th Surge VI (m^3)	7th Surge SR (m^3)	7th Surge VI (m^3)	8th Surge SR (m^3)	8th Surge VI (m^3)	9th Surge SR (m^3)	9th Surge VI (m^3)	10th Surge SR (m^3)	10th Surge VI (m^3)
150/1.0	0.5	4.5	2.058	2.442																		
10/0.5	0.5	2.25	1.1776	1.072																		
16/0.5	0.5	0.24	0.122	0.119	0.19	0.05	0.2	0.05	0.21	0.03	0.21	0.04	0.2	0.05	0.2	0.05	0.19	0.05	0.2	0.04	0.12	0.13
20/0.5	1.0	0.6	0.27	0.331	0.45	0.15	0.5	0.1	0.5	0.1	0.5	0.1	0.522	0.08	0.52	0.08	0.54	0.06				
30/0.5	0.5	0.45	0.211	0.24	0.22	0.23	0.23	0.22	0.35	0.1	0.39	0.06										
40/0.5	0.5	0.6	0.422	0.28	0.46	0.14	0.5	0.11	0.49	0.11												
50/0.5	0.5	0.75	0.44	0.32	0.6	0.15	0.61	0.14														
60/0.5	0.5	0.9	0.26	0.64	0.58	0.32	0.63	0.27														
150/1.0	1.0	9.0	6.02	2.98																		
10/0.5	1.25	2.25	1.382	0.868																		
50/0.1	2.5	0.75	0.334	0.417	0.512	0.238	0.589	0.1612														
50/0.2	1.25	0.75	0.23	0.52	0.48	0.28	0.47	0.28														
50/0.3	0.83	0.75	0.15	0.6	0.37	0.38	0.4	0.35														
50/0.4	0.625	0.75	0.23	0.52	0.44	0.32	0.49	0.26														
50/0.6	0.42	0.75	0.282	0.47	0.53	0.23	0.56	0.19														
50/0.7	0.36	0.75	0.09	0.66	0.36	0.39	0.4	0.39														
50/0.8	0.313	0.75	0.211	0.54	0.33	0.42	0.41	0.34														
50/0.9	0.275	0.75	0.256	0.494	0.36	0.39	0.44	0.32														
150/1.0	2.25	2.25	0.22	2.03																		

* Cycle Time/Cycle ratio .

Qo = Original Discharge.

VA = Volume Applied.

SR = Surface Runoff.

VI = Infiltrated Volume.

Table 4.-Volumes Applied , Surface Runoff, And Infiltrated Volumes For Different Runs And Surges At Site A.

the same amount of water would be entered the soil each time leading to almost constant surface runoff after the third surge.

The surface runoff hydrographs illustrated in figures 14 to 17 are example runs from site B. Surge flow runs had higher discharge peak values than companion continuous flow, which agree with the reports in the litreature (7). Bishop, et al. (2) demonstrated that the first runoff surge peaked at 0.0833 lps, the second at more than 0.167 lps, with subsequent surge flow runoff peaks at about 0.217 lps. The treatment used (40/0.5) with a discharge of 0.3 lps delivered to the head of the furrow. Coolidge, et al. (7) concluded that the runoff rate (0.05 - 0.067 lps) for continuous flow treatment remained at about one-third the rate of the surge flow treatments (0.183 -0. 217 lps). The difference in runoff discharge peak values between the first and the second surges was high (figurs 14 to 17). This difference decreased substantially when the second and the third surface runoff surges were considered. Beyond the third and subsequent surface runoff surges the difference is negligible as would be expected.

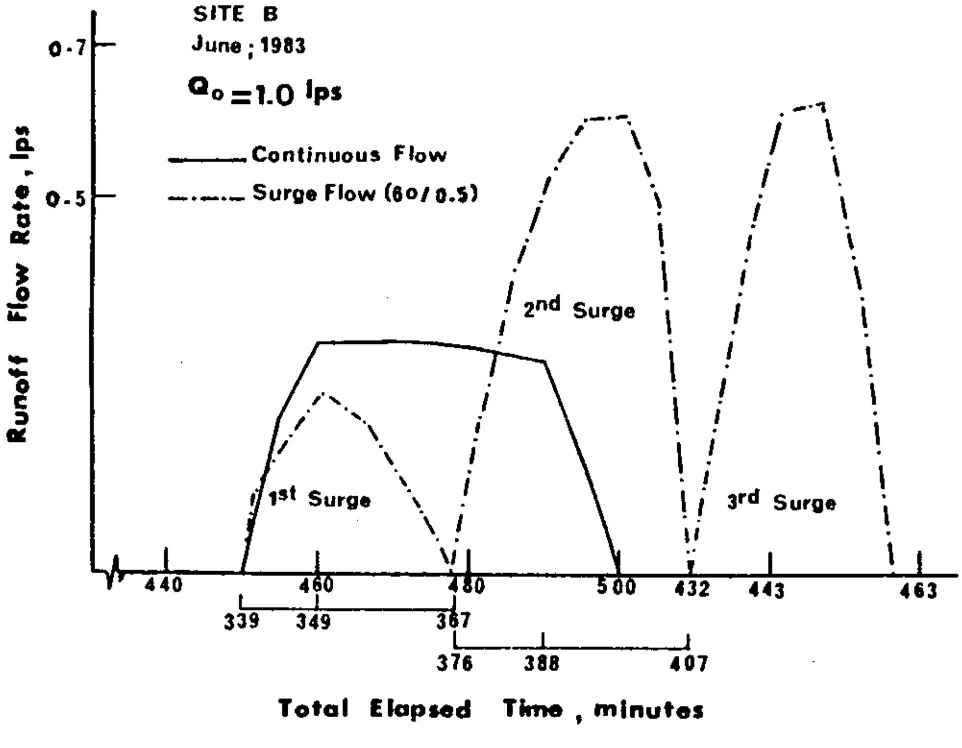

FIG.14.— Surface Runoff Hydrographs Under Continuous and Surge Flow Regimes.

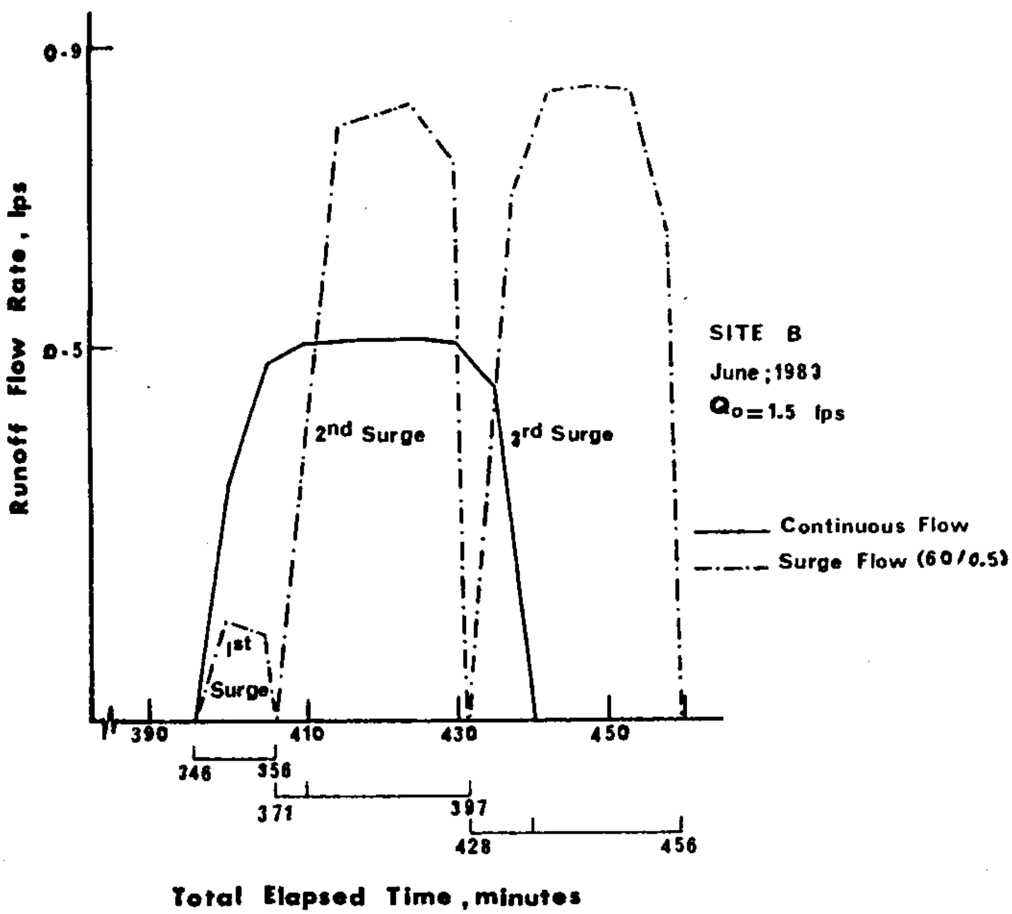

FIG.15.— Surface Runoff Hydrographs Under Continuous and Surge Flow Regimes.

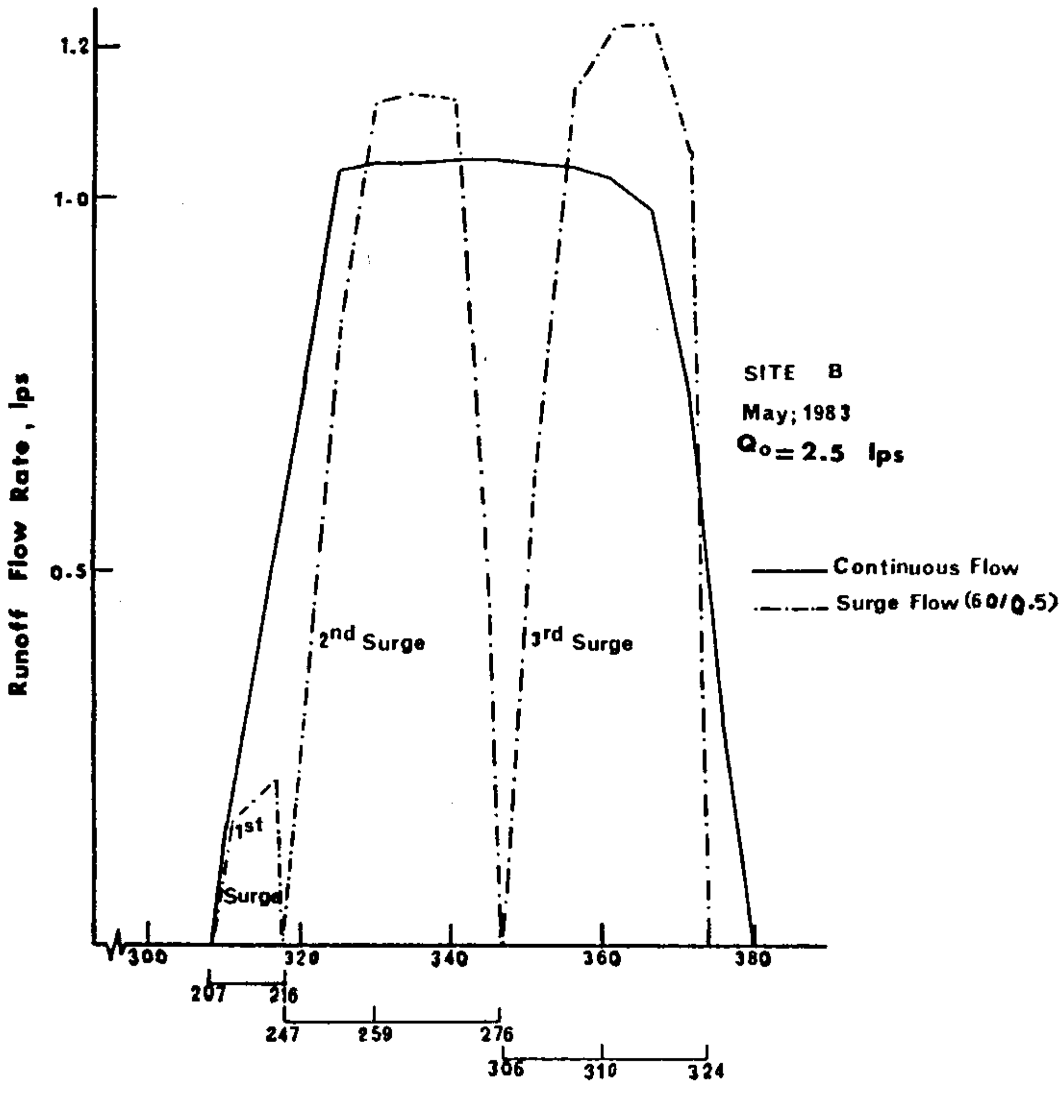

FIG.17.— Surface Runoff Hydrographs Under Continuous and Surge Flow Regimes.

The runoff peak value increased with the increase in the discharge delivered to the field inlet and the cycle and on times (figures 14 to 17). For a discharge of 1.0 lps the runoff discharge peak valuesare 0.305, 0.63, 0.77, and 0.64 lps under continuous, 60, 90 and 120 minutes cycle times surges, respectively. The peak runoff discharge values for 1.5 lps are 0.515, 0.85, 0.815, and 0.9 lps under continuous, 60, 90, and 120 minutes cycle time surges, respectively. In case of 2.0 lps the runoff discharge peak values are 0.745, 1.19, 1.2, and 1.19 lps under continuous, 60, 90, and 120 minutes cycle times surges, respectively. The peak runoff discharge values for 2.5 lps are 1.065, 1.245, 1.37, and 1.475 lps under continuous, 60, 90, and 120 minutes cycle time surges, respectively. The above results indicate that, the volume of water infiltrated through furrow under surge flow treatments was less than that under companion continuous flow. In other words infiltation rate under surge flow is less than that under continuous flow. Also, larger volumes of water are available at the end of surged furrows than that of continuous flow with equal opportunity times.

Distribution Uniformity

The low-quarter distribution uniformity (DULQ), defined as the average volume infiltrated into the least watered quarter of the furrow divided by the average volume infiltration into the entire furrow was evaluated. The distribution uniformity based on the volume infiltrated at the end of the furrow (DUEF), defined as the volume infiltrated into the last one meter of the furrow divided by the average volume infiltration into the entire furrow was also evaluated.

Volumes of water infiltrated are calculated using opportunity times in the infiltration function (Eqs. 11 and 12). Calculating DULQ and DUEF for these runs is illustrated in the following example.

Example

For the runs illustrated in figure 9, calculate DULQ and DUEF.

Solution

From figure 9 ,12 different points along the furrow were selected and tabulated as follows

Distance From Field Inlet (m)	0	20	40	60	80	100
Opportunity Time (minutes)	361	360	356	346	333	314
z (m^3/ m)	0.1432	0.1429	0.1416	0.1382	0.1339	0.1275
Distance From Field Inlet (m)	120	140	160	180	200	220
Opportunity Time (minutes)	293	258	215	169	109	40
z (m^3/ m)	0.1204	0.1083	0.0932	0.0766	0.0558	0.0246

The values of z were calculated by inserting the values of the opportunity time into Eq. 11 to yield the volumes of infiltrated water along the furrow.

Averge volumes of water infiltrated into furrow and least watered quarter were computed from the data tabulated above. Then, DULQ and DUEF would be

$$DULQ = \frac{0.0514}{0.1087} \times 100 = 47.29 \%$$

$$DUEF = \frac{0.0246}{0.1087} \times 100 = 22.63 \%$$

From figure 9 opportunity time for each surge is found, then used in the infiltration function (Eqs. 11 and 12). Continuous flow infiltration function is used when the soil was initally dry, while surge flow infiltration function is used when the soil was initially wet. At the head of the furrow opportunity times would be 60, 61, 60, and 61 minutes for the first, second, third, fourth, and fifth surge, respectively. The infiltrated volumes would be

$$z_{c1} = 0.001517\ (60)^{0.636} + 0.0002189 \times 60$$
$$= 0.0336\ m^3/m.$$
$$z_{s2} = 0.00305\ (61)^{0.311} + 0.000112 \times 61$$
$$= 0.0178\ m^3/m.$$

where z_{c1} = volume infiltrated from the first surge using continuous flow infiltration function; z_{s2} = volume infiltrated from the second surge using surge flow infiltration function; and z_{s3} = volume infiltrated from the third surge flow using surge flow infiltration function such that the infiltrated volumes at the end of the field would be 0.0246 m^3/m for comparison. Treating the points along the furrow by the same manner would end with the following table

Distance From Field Inlet (m)	0	20	40	60	80	100
z (m^3/m)	0.0652	0.0649	0.063	0.0581	0.0501	0.0396

Distance From Field Inlet (m)	120	140	160	180	200	220
z (m^3/m)	0.0466	0.0396	0.0276	0.0246	0.0246	0.0246

Average volumes of water infiltrated into the furrow and least watered quarter were calculated from the above data. Then, DULQ and DUEF would be

$$DULQ = \frac{0.0253}{0.044} \times 100 = 57.50\ \%$$

$$DUEF = \frac{0.0246}{0.044} \times 100 = 55.91\ \%$$

Infiltrated volumes of water expressed in m^3/m with distance from field inlet are shown in figures 18 through 22. Volumes infiltrated at the end of the field are 0.0246 m^3/m in all cases for comparison. Relatively high difference between infiltrated volumes of water under continuous and surge flow along the furrows. This difference is due to the shorter advance phase under surge flow using only about half of water being used by continuous flow. This will be ended with little differences in infiltrated volumes of water along the furrow. The values of DULQ and DUEF are higher in all cases in surge flow runs than the companion continuous flow.

The 1.0 lps runs (figure 18) indicate that less water is needed (about half) by surge flow so that the infiltrated volumes at the end of the field are 0.0246 m^3/m . In addition to that DULQ for surge flow are 54.2 %, 59.64 % , and 66.29 % under 60, 90, and 120 minutes cycle time surges, respectively. DULQ of continuous flow is 50.12% DUEF are 19.54%, 42.2%. 44.73, and 40.26% for continuous, 60, 90, and 120 minutes cycle time surges, respectively.

The 1.5, 2.0, and 2.5 lps runs showed similar trend to 1.0 lps results above. Walker, et al. (30) DULQ values ranged from 77 % for the 480 and 30 minute cycle time to 81 % for the 120 minute cycle. Their DULQ values for continuous flow regimes ranged from 88 % for the six hour application to 72 % for the three hour applications where the field was divided into two equal halfs. Thus, the DULQ achieved by irrigating the field in half is approximately equal to the surge flow treatment on full length furrow.

If the desired volume of infiltrated water at the end of the field is increased, then DULQ and DUEF will increase also. The infiltration rate will be higher at the last quarter of the field as basic infiltration rate has not reached yet . Also, the wetted perimeter of the furrow at the last quarter

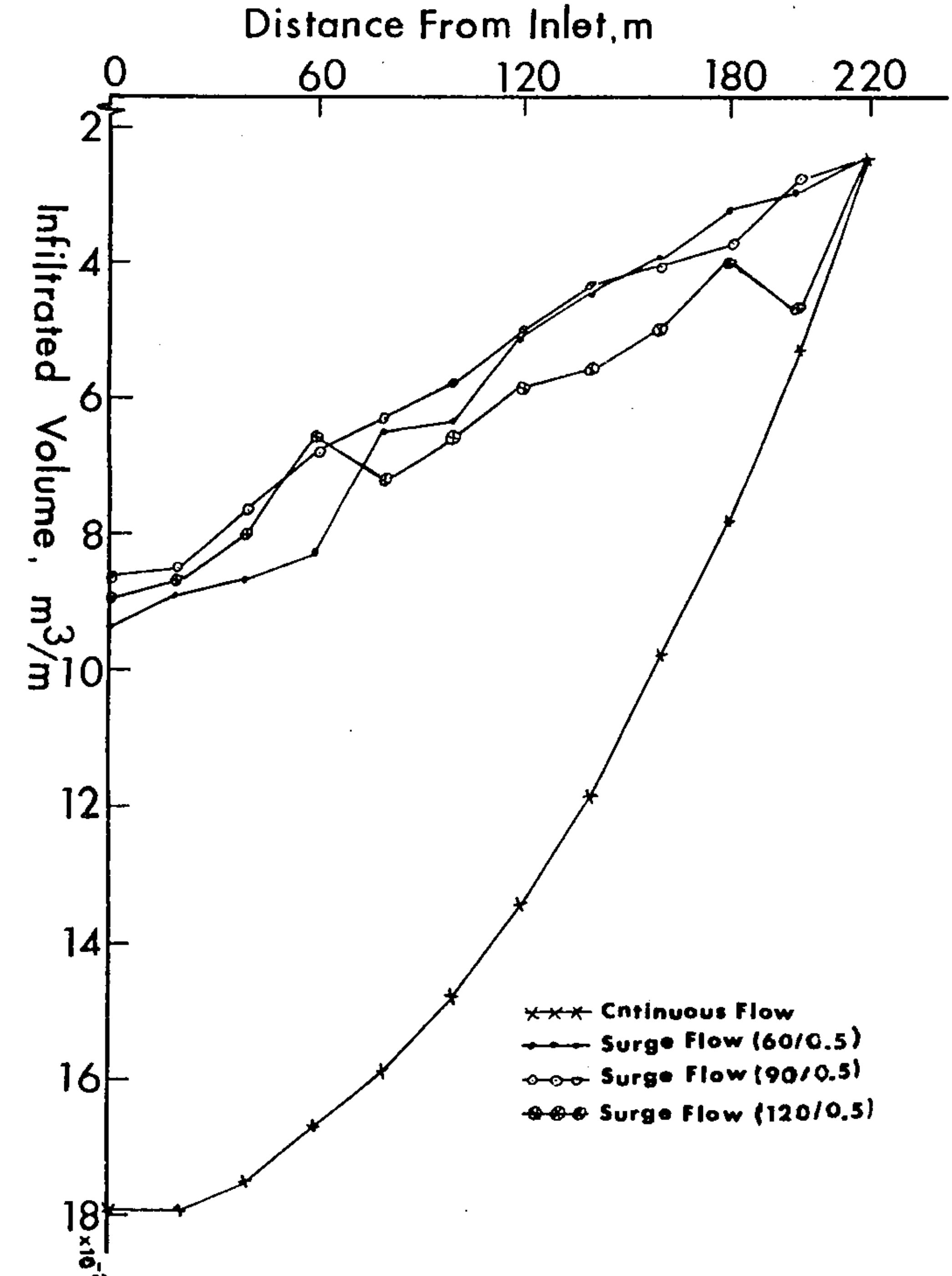

Fig. 18.- Infiltrated Profiles under Continuous and Surge Flow Practices of 1.0 lps.

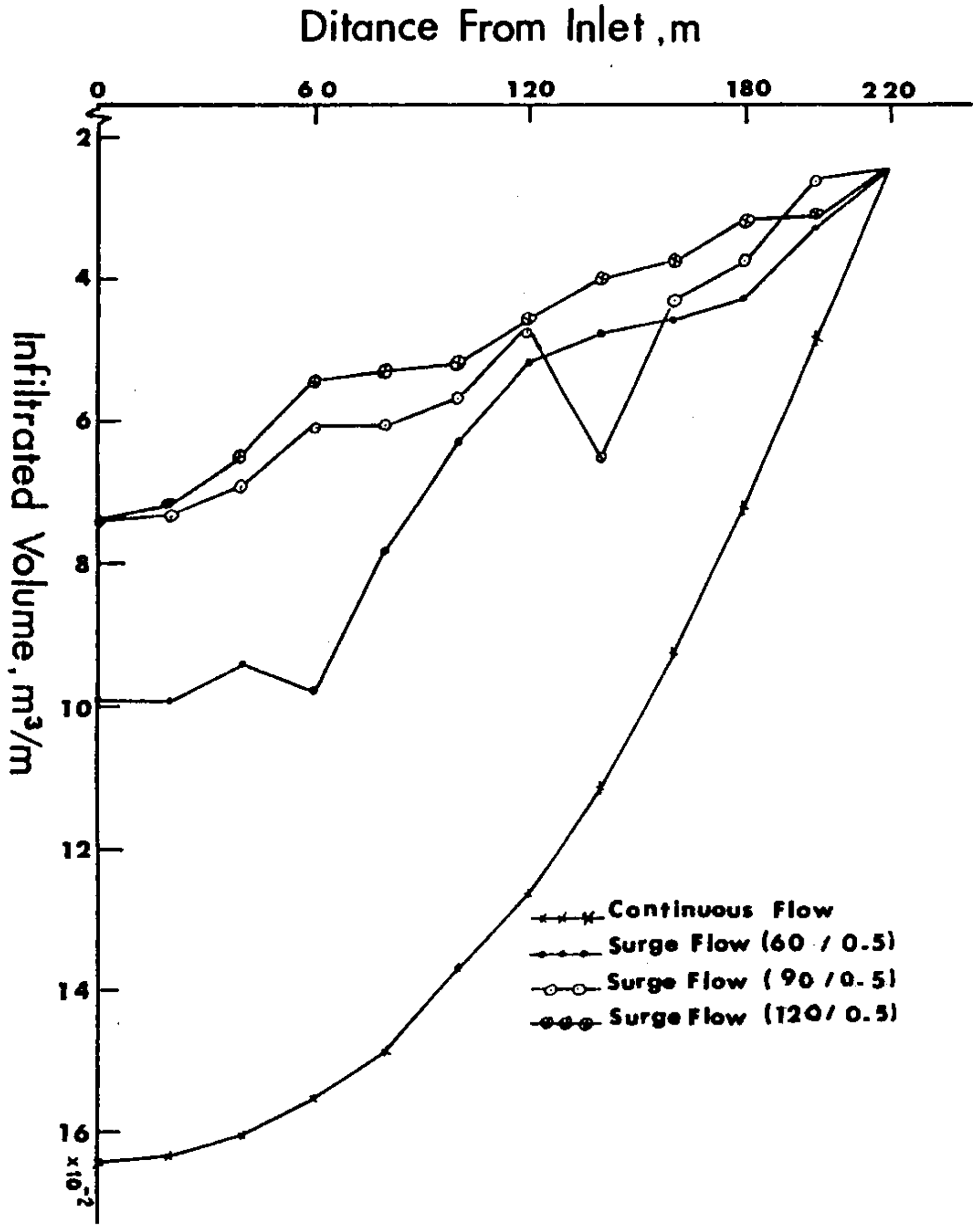

Fig. 19.- Infiltrated Profiles under Continuous and Surge Flow Practices of 1.5 lps.

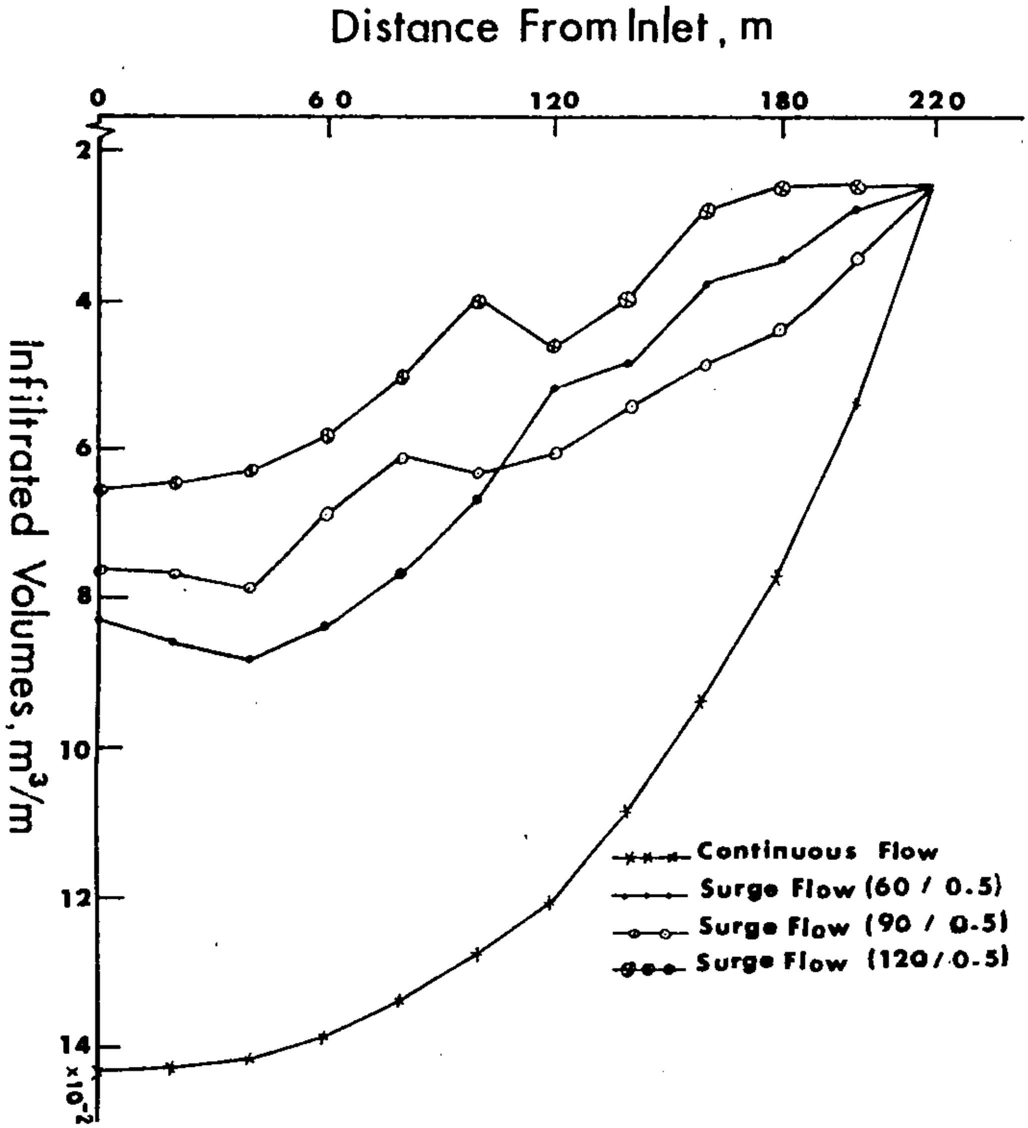

Fig. 20.- Infiltrated Profiles under Continuous and Surge Flow Practices of 2.0 lps.

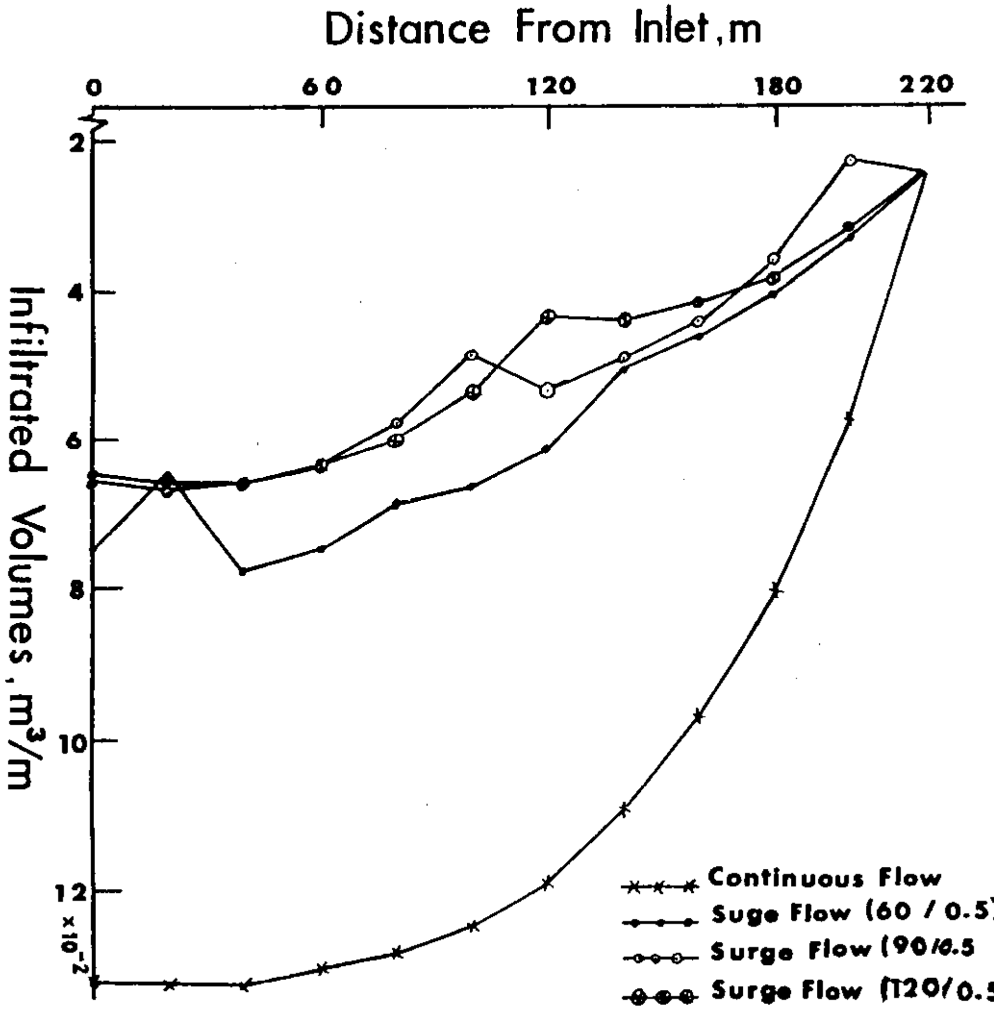

Fig. 21.- Infiltrated Profiles under Continuous and Surge Flow Practices of 2.5 lps.

would increase with time as the amount of water increases . The above conclusion is obtained by comparing figure 18 with figure 22 where the difference between these two runs is only the desired volume at the end of the field. For 1.0 lps runs (table 5), all DULQ and DUEF increased significantly by increasing the volume infiltrated into the last one meter end of the furrow length from 0.0246 m^3/m to 0.05 m^3/ m .

No difference between continuous and surge flow runs at site A. This is due to mangement factors.

Application Efficiency

Application efficiency Ea, is defined as the volume of water stored in the root zone divided by the volume of water applied. Ea is highly dependent on the required depth of application. The efficiency figures were calculated on the assumption that the required depth of application is 0.05 m^3/m for all treatments. This is equivalent to 50mm depth on a wetted area of 1 m between furrows.

Table 6 shows application efficiencies for different runs at site B. Infiltrated volumes into the last one meter of the field length was 0.0246 m^3/m in each run. Application efficiency was calculated considering accumulative amount of water equal to 0.05 m^3/m is required. This amount equal to 50mm

Table 5.-Distribution Uniformities (DULQ And DUEF) For Surge And Continuous Flow Runs At Site B.

Qo (lps)	Run *	Vend (m^3/m)	DULQ	DUEF
1.0	Continuous	0.0246	41.85	19.54
	60/0.5	0.0246	52.71	42.20
	90/0.5	0.0246	57.85	44.73
	120/0.5	0.0246	64.47	44.26
1.5	Continuous	0.0246	43.20	21.04
	60/0.5	0.0246	54.61	38.14
	90/0.5	0.0246	59.89	46.59
	120/0.5	0.0246	63.93	50.51
2.0	Continuous	0.0246	47.29	22.63
	60/0.5	0.0246	51.40	41.77
	90/0.5	0.0246	64.30	42.78
	120/0.5	0.0246	55.91	55.91
2.5	Continuous	0.0246	51.13	23.21
	60/0.5	0.0246	61.40	43.23
	90/0.5	0.0246	62.35	49.30
	120/0.5	0.0246	69.37	49.40
1.0	Continuous	0.0500	48.86	34.18
	60/0.5	0.0435	62.47	53.84
	90/0.5	0.0394	63.42	54.78
	120/0.5	0.0500	75.10	58.21

* CYCLE TIME / CYCLE RATIO

Vend = Volume infiltrated into the last one meter of the furrow length (m^3/m).

It was found that infiltration rate was lower under surge flow runs which caused a higher volume of runoff measured under these conditions over the continuous flow. Distribution uniformity and application efficiency were improved under surge flow conditions.

The results of these experiments reinforced the argument that surge flow irrigation is an improved practice of surface irrigation and may cause a great save of water and energy resources.

Recommendations

Surge flow experiments under new field conditions are to be explored. So that, its further behavior can easily be studied. Surface seal development and ifiltration changes to be explored also. This might include developing a computer program for predicting surface seal development. This is expected to help in better explanation and dealing with surge flow practice.

Detailed study of surge flow parameters would be valuable,especially if its unique effect is known. Surge flow proper design procedure inhereted from soil and field conditions needed to simplify use of this new practice and its benefits. Also, an evaluation procedure development would be required.

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Table 8- Inflow - Outflow Data For Infiltration Rate Measurement Under Continuous and Surge Flow At Site A.

Continuous Flow			Surge Flow		
Time (min)	Inflow (lps)	Outflow (lps)	Time (min)	Inflow (lps)	Outflow (lps)
5	1.17	1.117	5	1.17	1.127
10	= =	1.125	10	= =	1.135
15	= =	1.128	15	= =	1.139
20	= =	1.129	20	= =	1.139
25	= =	1.130	25	= =	1.140
30	= =	1.131	30	= =	1.140
35	= =	1.132	35	= =	1.140
40	= =	1.132	40	= =	1.141
45	= =	1.133	45	= =	1.141
50	= =	1.133	50	= =	1.141
55	= =	1.133	55	= =	1.141
60	= =	1.133	60	= =	1.142
65	= =	1.134	65	= =	1.142
70	= =	1.134	70	= =	1.142
75	= =	1.138	75	= =	1.142
100	= =	1.134	100	= =	1.147
240	= =	1.139	300	= =	1.143
250	= =	1.139	400	= =	1.143
350	= =	1.139	540	= =	1.143
480	= =	1.139	600	= =	1.143
540	= =	1.139	1440	= =	1.142
1295	= =	1.136			

Table 10.- Advance and Recession Data for Continuous Flow Runs.

Distance	1.0 lps		1.5 lps		2.0 lps		2.5 lps	
(m)	AT	RT	AT	RT	AT	RT	AT	RT
00	00.0	484.0	00.0	433.1	00.0	360.3	00.0	360.2
10	01.5	486.1	01.5	435.0	01.1	362.8	01.2	362.0
20	05.6	488.2	05.8	436.2	02.9	363.9	02.0	364.1
30	13.5	490.0	09.0	437.0	05.0	364.8	04.0	366.0
40	23.0	492.0	17.5	438.1	08.5	365.6	06.1	368.0
50	35.9	493.9	25.2	439.0	15.1	367.5	10.0	369.2
60	51.7	494.2	35.9	439.5	22.5	368.7	13.5	370.1
70	63.2	496.0	48.1	440.0	30.1	370.1	19.1	372.0
80	77.4	496.3	63.3	440.0	39.2	372.0	24.0	373.8
90	94.0	498.0	78.0	441.0	48.3	372.8	30.0	375.1
100	113.0	500.0	92.1	942.0	58.0	373.3	37.9	377.2
110	131.3	500.0	105.5	442.0	71.1	374.1	45.0	377.0
120	156.8	501.1	130.2	441.9	83.6	374.8	56.0	377.9
130	178.0	501.2	144.8	441.9	98.1	376.4	71.0	378.0
140	203.5	502.0	164.7	442.0	119.0	377.5	85.1	379.0
150	232.7	502.0	200.9	441.8	142.1	378.1	102.3	380.0
160	268.6	502.0	229.1	442.0	163.1	379.6	123.1	380.0
170	283.3	502.1	245.8	442.0	190.0	381.0	144.0	380.2
180	319.3	503.0	280.7	441.5	213.2	382.8	168.0	380.3
190	352.0	503.0	306.0	441.9	243.1	384.2	201.5	379.8
200	384.8	502.2	338.6	441.6	276.3	384.9	232.0	380.1
210	417.1	501.8	368.7	441.0	313.2	385.5	265.1	380.0
220	450.0	497.0	395.1	440.0	346.0	386.6	308.2	379.0

AT = Advance Time (minutes).
RT = Recession Time (minutes).

Data For Continuous Flow Runs.

Table 11.- Advance and Recession Data for Surge
Flow of 1.0 lps Discharge and 60 minutes
Cycle Time and 0.5 Cycle Ratio.

Distance	1st S		2nd S		3rd S		4th S		5th S		6th S	
(m)	AT	RT	AT	RT	AT	RT	AT	RT	AT	RT	AT	RT
00	00.0	45.0	90.0	135.0	180.0	229.1	270.0	315.1	360.0	404.1	450.0	495.6
10	01.5	45.7	91.8	136.0	180.3	331.0	271.4	315.7	360.5	404.8	450.3	496.0
20	05.6	46.4	93.2	138.1	181.1	332.0	271.4	317.1	361.0	405.1	450.7	496.6
30	13.5	47.0	94.3	138.6	183.4	333.1	272.1	318.3	361.9	405.3	451.2	497.0
40	23.0	47.5	95.7	138.9	184.9	334.0	272.7	319.1	362.4	405.7	451.5	497.7
50	34.6	47.9	97.4	139.5	187.1	335.2	273.8	320.1	363.1	406.3	452.0	498.2
51.5	38.0	48.2										
60			100.2	139.9	189.2	336.0	275.3	320.9	364.2	405.4	452.1	498.8
70			104.1	140.2	191.7	336.0	276.8	321.5	363.5	405.6	452.6	499.2
80			110.5	141.0	193.9	337.0	278.1	322.7	366.2	405.8	452.9	499.8
90			118.2	141.8	195.0	337.9	279.4	323.3	366.3	405.9	453.4	501.0
100			134.3	142.1	196.2	338.0	281.0	324.3	366.8	405.9	453.8	501.8
110					200.8	339.0	282.7	325.6	367.1	406.2	454.1	502.6
120					204.8	338.8	284.3	326.9	367.3	406.0	454.8	503.4
130					211.1	338.0	285.8	327.9	367.4	405.9	455.6	504.3
140					215.8	337.7	287.2	330.0	367.5	405.2	456.1	505.9
150					222.3	336.0	288.2	331.2	367.6	406.1	457.2	506.8
160					227.0	332.0	289.5	332.1	367.8	406.3	457.9	507.0
170							291.4	333.0	369.1	406.5	458.5	507.5
180							295.0	334.2	369.7	406.8	459.4	508.1
190							298.1	335.1	370.2	406.9	460.2	508.6
200							304.0	335.8	371.9	407.1	460.7	509.3
210							313.0	337.0	372.0	408.0	461.0	509.8
220							324.0	338.0	372.3	410.0	461.4	509.9

S = Surge.
AT = Advance Time (minutes).
RT = Recession Time (minutes).

Data For Figure 1.

Table 13.- Advance and Recession Data for Surge Flow of 1.0 lps Discharge and 120 minutes Cycle Time and 0.5 Cycle Ratio.

Distance	1st S		2nd S		3rd S		4th S		5th S		6th S	
(m)	AT	RT	AT	RT	AT	RT	AT	RT	AT	RT	AT	RT
00	00.0	60.0	120.0	188.0	240.0	300.0	360.0	420.0	480.0	540.2	600.0	660.1
10	01.5	50.3	120.7	190.1	241.1	302.7	360.2	421.0	480.2	540.8	600.2	660.4
20	05.6	61.1	121.8	192.3	242.1	302.5	360.9	422.2	480.8	541.5	600.4	660.6
30	13.5	62.0	123.2	195.0	242.8	304.4	351.8	422.9	481.0	541.9	600.6	660.7
40	23.0	62.5	125.2	197.2	243.0	306.9	361.9	423.4	481.2	542.3	600.9	660.8
50	35.9	63.0	128.4	198.8	243.5	307.4	361.9	424.8	481.4	543.0	601.0	660.9
60	51.5	63.2	131.5	200.0	244.4	307.9	362.0	425.7	481.5	543.4	601.2	661.1
70	63.2	63.9	135.2	201.9	245.0	308.1	362.2	427.1	481.6	544.0	601.3	661.2
80			141.4	203.0	245.5	309.0	362.9	428.9	481.7	544.2	601.4	661.3
90			151.5	204.0	246.0	310.8	363.2	431.7	481.9	544.8	601.5	661.4
100			164.5	205.6	247.0	312.8	365.0	433.4	482.2	545.4	601.7	661.5
110			171.5	206.8	247.9	313.6	365.9	436.0	482.9	545.6	601.8	661.6
120			177.8	208.0	248.6	314.0	366.2	437.5	483.5	545.7	602.0	661.7
130			187.6	208.0	251.2	314.6	367.0	439.2	484.2	545.9	602.3	661.8
140			203.9	206.0	254.0	314.8	368.0	440.8	484.9	546.3	602.8	661.9
150					258.3	315.0	369.0	441.6	485.4	546.7	603.5	662.1
160					265.2	315.3	371.8	442.0	486.2	547.1	603.9	662.3
170					273.4	316.0	375.0	442.5	488.5	547.5	604.6	662.4
180					283.0	315.8	380.0	443.1	489.2	548.3	605.3	662.1
190					296.8	313.0	387.0	443.6	492.5	548.9	605.8	661.3
198.9					309.0	310.0						
200							393.2	444.0	493.6	549.0	606.2	660.1
210							401.0	446.0	493.9	550.1	606.8	660.2
220							410.0	447.0	494.5	550.5	607.7	660.9

S = Surge.
AT = Advance Time (minutes).
RT = Recession Time (minutes).

Data For Figure 3.

Table 16.- Advance and Recession Data for Surge Flow of 1.5 lps Discharge and 120 minutes Cycle Time and 0.5 Cycle Ratio.

Distance	1st S		2nd S		3rd S		4th S		5th S	
(m)	AT	RT	AT	RT	AT	RT	AT	RT	AT	RT
00	00.0	60.0	120.0	180.0	240.0	300.0	360.0	420.0	480.0	540.0
10	01.5	61.7	121.2	181.2	241.0	301.5	360.2	420.8	480.1	540.3
20	05.8	62.2	121.8	182.4	241.8	302.0	360.8	421.2	480.2	540.4
30	09.9	62.7	122.0	183.0	242.1	302.5	361.0	422.3	480.3	540.6
40	17.5	63.4	123.0	183.9	242.6	303.5	361.3	423.6	480.5	541.2
50	25.2	63.8	125.5	184.8	243.5	304.5	361.9	423.5	480.6	542.2
60	35.9	64.2	127.9	185.6	245.6	305.5	362.3	423.7	480.7	543.3
70	48.1	64.5	129.4	186.5	247.3	307.0	362.4	423.9	480.9	543.4
80	63.3	65.1	132.6	187.0	249.1	308.5	362.6	423.4	481.2	543.5
90			137.9	187.7	250.5	310.6	362.8	424.5	481.4	543.5
100			143.2	189.0	251.5	312.4	363.1	424.3	481.6	543.6
110			147.7	189.6	252.6	314.2	363.3	424.5	481.7	543.8
120			153.4	190.1	254.0	315.4	363.5	424.6	481.9	544.0
130			165.6	191.8	255.7	317.3	364.6	425.2	483.1	544.3
140			183.8	192.6	257.1	319.3	364.9	425.3	485.3	543.8
150					259.7	320.5	365.3	424.1	486.4	543.7
160					262.6	321.4	366.4	424.3	488.6	543.6
170					265.6	322.2	367.3	425.6	489.7	543.8
180					268.5	322.8	368.9	426.7	491.3	543.9
190					272.1	323.2	369.4	425.9	492.2	542.1
200					276.9	323.6	370.6	424.5	493.1	543.2
210					284.0	324.1	371.3	423.3	494.3	543.3
220					292.0	323.3	372.7	423.0	495.2	542.8

S = Surge.
AT = Advance Time (minutes)
RT = Recession Time (minutes).

Data For Figure 6.

Table. 17.- Advance and Recession Data for Surge Flow of 2.0 lps Discharge and 60 minutes Cycle Time and 0.5 Cycle Ratio.

Distance	1st S		2nd S		3rd S		4th S		5th S		6th S		7th S		8th S	
(m)	AT	RT	AT	RT	AT	RT	AT	RT	AT	RT	AT	RT	AT	RT	AT	RT
00	00.0	30.5	60.0	91.0	120.0	151.3	180.0	212.0	240.0	274.0	300.0	331.0	360.0	390.0	420.0	450.0
10	01.1	33.6	61.0	93.0	120.3	152.0	180.2	214.0	241.0	276.1	300.8	333.0	360.5	390.5	420.9	450.1
20	02.9	35.5	61.5	95.6	121.0	154.0	181.0	216.0	241.7	276.5	301.0	335.0	361.1	391.1	421.5	451.5
30	05.0	36.4	62.0	97.0	121.9	156.0	181.9	218.0	242.0	301.3	337.0	362.2	362.2	392.0	422.0	452.2
40	08.5	37.7	63.0	98.0	122.0	157.0	182.0	220.0	242.2	280.0	302.0	339.2	362.5	392.2	422.6	453.5
50	15.1	38.4	64.0	99.0	122.5	158.0	182.2	222.1	243.2	282.0	302.3	342.0	363.2	292.1	423.5	453.9
60	22.6	38.9	62.0	100.0	123.0	159.8	183.0	223.9	244.0	284.0	302.9	343.9	364.5	393.4	423.7	454.6
70	30.1	40.7	66.0	101.0	124.0	160.9	184.0	224.0	245.0	287.1	303.2	345.6	364.8	393.2	424.3	454.9
80	33.6	41.2	67.3	101.2	125.2	161.8	184.5	225.0	245.6	288.0	303.9	347.0	365.0	393.9	425.1	455.6
90			69.2	101.3	126.0	162.0	185.0	228.5	246.0	289.0	304.0	349.0	365.3	394.3	426.0	456.1
100			77.5	101.0	128.0	162.0	186.0	228.0	246.2	290.0	305.0	351.0	365.9	394.8	427.2	456.3
110			85.2	100.0	132.8	163.0	186.5	228.1	246.9	291.0	306.0	352.0	366.4	395.2	428.2	456.9
120			96.1	98.0	139.9	164.0	187.6	219.2	247.5	291.9	306.3	353.0	366.9	395.3	429.1	457.5
130					149.9	164.0	190.0	229.3	247.9	293.0	307.0	355.2	367.2	395.5	429.5	457.9
140					158.0	161.9	192.3	229.0	248.3	294.0	308.0	356.0	368.0	395.7	429.9	457.9
150							194.0	229.0	251.0	295.0	309.0	357.9	368.3	396.0	430.2	459.3
160							199.8	228.0	254.0	295.6	309.5	358.0	369.0	396.3	430.8	458.5
162							207.1	225.0								
170							217.0	226.0	259.0	296.0	310.2	360.0	370.5	396.9	431.2	458.7
180							221.0	227.1	264.0	296.0	311.5	360.8	371.0	397.1	431.3	459.3
190									269.8	295.3	313.0	261.3	371.5	397.3	431.5	459.9
200									275.3	294.0	314.0	362.3	371.9	397.4	431.6	460.5
210									281.8	293.0	316.0	364.0	375.6	397.6	431.7	460.9
216									287.3	290.0						
220											319.0	364.5	377.3	397.9	431.9	461.8

S = Surge.
AT = Advance Time (minutes).
RT = Recession Time (minutes).
Data For Figure 7.

Table 18.- Advance and Recession Data for Surge Flow of 2.0 lps Discharge and 90 minutes Cycle Time and 0.5 Cycle Ratio.

Distance	1st S		2nd S		3rd S		4th S		5th S		6th S	
(m)	AT	RT	AT	RT	AT	RT	AT	RT	AT	RT	AT	RT
00	00.0	46.0	90.0	138.0	180.0	227.0	270.0	31.0	360.0	405.0	450.0	495.0
10	01.1	46.1	91.0	138.1	180.6	229.0	270.2	317.0	361.1	405.2	450.2	495.3
20	02.9	47.0	91.5	139.0	181.0	231.0	270.4	319.0	361.9	405.0	450.3	495.6
30	05.0	47.3	91.9	139.8	181.9	232.0	270.5	321.0	362.2	406.0	450.6	495.9
40	08.5	47.9	92.0	140.0	182.0	233.0	270.4	322.0	362.8	406.5	450.7	495.9
50	15.1	48.0	92.2	141.0	182.2	234.0	271.5	323.0	363.3	407.0	451.2	496.3
60	22.6	49.0	93.0	141.8	182.4	236.0	271.0	323.8	363.8	407.2	451.7	496.4
70	30.1	50.0	93.4	142.0	182.8	236.2	273.0	324.0	364.1	407.6	451.9	496.5
80	39.2	51.0	93.8	142.0	183.0	237.4	273.0	325.0	364.9	407.8	452.1	497.2
90	48.3	52.0	94.0	142.0	183.6	238.0	274.0	325.0	365.6	407.9	452.3	497.5
96	52.0	52.0										
100			95.0	142.0	184.0	239.0	274.6	325.9	365.9	408.3	452.8	497.8
110			98.0	141.6	184.2	240.0	776.0	326.0	366.1	408.5	453.5	497.9
120			102.0	142.0	184.6	241.0	277.0	326.1	366.8	408.5	453.8	498.0
130			108.2	141.5	185.0	241.8	278.0	327.0	367.3	408.5	453.9	498.2
140			114.0	140.3	185.3	242.0	278.3	328.0	367.8	409.2	454.3	498.3
150			122.0	138.0	186.0	242.0	279.6	328.6	368.7	409.3	454.7	498.2
156.2			131.0	132.0								
160					190.0	242.0	280.0	329.0	369.1	409.7	455.2	498.6
170					194.0	242.0	281.8	330.0	369.7	409.8	455.4	499.2
180					200.0	241.9	283.0	331.0	370.2	410.5	455.6	499.5
190					208.0	241.3	289.0	331.4	370.9	411.0	455.7	499.9
200					217.0	241.0	291.0	332.0	371.4	412.2	456.3	500.2
210					228.3	241.0	295.0	323.0	372.5	412.5	456.2	501.1
216					240.0	240.5						
220							299.0	324.0	372.8	412.9	456.9	501.8

S = Surge.

AT = Advance Time (minutes) .

RT = Recession Time (minutes).

Data For Figure 8.

Table 19.- Advance and Recession Data for Surge Flow of 2.0 lps Discharge and 120 minutes Cycle Time and 0.5 Cycle Ratio.

Distance	1st S		2nd S		3rd S		4th S		5th S	
(m)	AT	RT	AT	RT	AT	RT	AT	AR	AT	AR
00	00.0	60.0	120.0	180.0	240.0	300.0	360.0	420.0	480.0	540.0
10	01.1	61.0	121.0	181.0	241.0	301.0	360.2	420.2	480.2	540.2
20	02.9	62.0	121.3	182.0	241.8	301.9	360.9	420.3	480.8	540.2
30	05.0	63.0	122.0	183.4	242.0	302.0	361.5	420.5	481.5	540.3
40	08.5	63.9	123.0	184.0	243.0	303.0	361.8	421.6	482.2	540.9
50	15.1	64.0	123.5	185.0	243.4	304.0	361.9	421.8	482.6	541.1
60	22.6	64.2	124.0	186.0	244.0	305.0	362.0	421.9	482.8	541.2
70	30.1	65.0	124.7	187.0	244.2	306.0	362.5	421.9	482.9	542.1
80	39.2	65.1	125.0	187.8	245.0	308.0	362.8	422.6	483.2	542.4
90	48.3	65.9	127.0	188.0	245.8	308.3	362.9	422.9	483.5	542.3
100	58.0	66.0	128.5	188.1	246.0	309.0	363.1	423.7	483.9	542.8
110	71.1	68.0	131.5	189.0	247.0	310.0	364.8	424.9	484.3	543.5
120			135.8	191.0	248.0	310.8	365.2	424.7	484.6	543.7
130			143.0	191.8	248.3	311.6	366.5	424.2	484.8	544.4
140			150.0	192.0	249.0	312.0	367.4	424.6	485.5	545.0
150			159.0	191.9	249.5	312.3	368.3	424.5	485.9	545.2
160			170.2	190.0	250.0	313.8	369.2	423.9	486.2	545.9
168.3			180.0	184.0						
170					251.8	314.0	370.2	424.2	486.7	546.0
180					252.2	315.0	371.4	423.6	487.0	544.2
190					254.0	316.5	372.3	424.1	487.2	543.2
200					256.0	318.0	373.2	423.2	487.3	543.1
210					260.0	319.8	374.1	423.1	487.6	543.1
220					264.3	321.0	375.0	423.0	488.2	543.0

S = Surge.

AT = Advance Time (minutes).

RT = Recession Time (minutes).

Data For Figure 9.

Table 20.- Advance and Recession Data for Surge Flow of 2.0 lps Discharge and 5o minutes Cycle Time and 0.5 Cycle Ratio.

Distance	1st S		2nd S		3rd S		4th S		5th S		6th S		7th S		8th S		9th S	
(m)	AT	RT	AT	RT	AT	RT	AT	RT	AT	RT	AT	RT	AT	RT	AT	RT	AT	RT
00	00.0	27.0	50.0	75.1	100.0	125.0	150.0	175.2	200.0	225.3	250.0	275.3	300.0	325.2	350.0	375.0	400.0	425.0
10	00.8	30.1	51.6	77.3	100.6	126.0	150.5	176.0	200.5	225.9	250.5	277.0	300.5	326.8	351.0	375.2	400.2	425.1
20	02.0	31.3	52.5	78.5	101.3	127.3	151.1	177.1	201.0	227.0	227.0	280.0	301.0	327.0	351.5	375.4	400.8	425.2
30	08.5	32.6	53.8	80.7	101.7	128.1	151.7	178.0	201.8	227.8	252.0	281.3	301.9	328.1	351.9	375.6	401.6	425.4
35.7	27.3	33.1																
40			56.5	81.7	102.5	129.3	152.3	178.9	202.3	228.6	252.2	283.1	302.1	328.4	352.5	376.2	401.9	425.9
50			65.4	82.2	103.7	130.7	153.4	179.[illegible]	203.2	229.0	253.0	285.2	302.9	328.9	353.2	376.9	402.2	426.3
60			71.2	82.5	105.8	130.9	155.1	180.8	204.9	229.9	254.0	287.0	303.8	329.7	353.9	377.5	402.5	426.9
70			78.3	81.3	108.0	131.8	157.7	181.6	206.8	232.0	255.1	288.1	304.9	331.0	354.2	378.0	402.7	427.1
80					114.1	132.5	158.9	182.5	207.6	233.8	257.0	290.0	306.0	331.9	355.2	378.2	402.9	427.2
90					120.0	133.1	159.2	183.0	209.0	235.9	258.1	291.0	307.2	332.8	355.8	378.4	403.1	427.3
100					125.0	133.1	160.0	183.2	209.7	237.1	259.0	292.2	308.5	334.5	356.2	378.3	403.2	427.9
110					133.8	134.1	161.5	184.1	210.9	239.0	200.0	293.5	309.5	335.0	357.2	378.9	403.7	427.9
120							167.7	185.0	212.0	241.0	261.6	295.7	310.2	335.1	358.5	379.5	413.8	428.2
130							174.5	185.1	212.9	242.0	262.0	297.1	311.0	336.5	359.6	379.8	404.2	428.8
134							178.3	185.3										
140									216.3	243.9	264.2	298.0	312.1	337.8	360.2	380.2	404.5	428.9
150									221.2	245.0	266.0	298.8	314.0	339.0	361.5	380.4	404.6	428.8
160									226.0	245.1	267.8	299.5	315.2	339.4	362.8	380.6	404.9	428.7
170									233.2	245.9	270.0	300.0	316.1	341.2	363.1	380.7	405.1	429.2
180									241.1	245.9	272.0	300.0	318.0	342.0	364.6	380.8	405.4	421.5
190											278.0	300.0	319.3	343.5	365.2	380.9	405.6	479.7
200											285.1	301.1	320.1	343.9	366.3	381.4	405.7	429.8
210											293.2	299.1	223.2	344.0	367.1	381.5	405.8	429.9
220													228.1	344.5	367.5	381.7	406.1	430.2
															368.1	381.9	406.8	430.4

S = Surge.
AT = Advance Time (minutes).
RT = Recession Time (minutes).

Data For Figure 10

Table 21.- Advance and Recession Data for Surge Flow of 2.5 lps Discharge and 60 minutes Cycle Time and 0.5 Cycle Ratio.

Distance	1st S		2nd S		3rd S		4th S		5th S		6th S	
(m)	AT	RT	AT	RT	AT	RT	AT	RT	AT	AR	AT	AR
00	00.0	31.8	60.0	94.0	120.0	151.0	180.0	211.0	240.0	270.0	300.0	330.0
10	01.2	33.8	61.1	95.0	121.0	153.0	180.2	212.0	240.2	270.3	300.2	330.2
20	02.1	35.0	61.9	96.7	121.8	154.8	181.0	214.0	240.6	270.5	300.3	330.4
30	04.0	36.6	62.0	98.0	122.0	156.0	181.6	215.1	240.7	270.6	300.5	330.6
40	06.1	37.9	62.4	100.0	122.8	156.4	181.8	216.3	241.3	271.2	301.2	330.6
50	10.0	38.0	62.8	100.8	123.2	157.9	182.0	217.1	241.6	271.8	301.4	330.8
60	13.5	38.5	63.0	101.0	124.0	158.3	182.4	218.2	242.5	272.1	301.5	330.9
70	19.1	38.0	63.5	101.6	125.0	159.0	183.0	219.4	243.6	272.8	301.8	331.2
80	24.0	38.0	64.0	102.0	126.0	159.9	184.6	220.0	244.7	272.9	302.3	331.9
88	32.0	33.0										
90			65.0	102.0	126.3	160.0	185.5	221.0	244.9	273.3	302.7	332.2
100			65.7	102.0	127.0	160.7	186.0	222.0	245.3	273.5	302.9	332.5
110			68.0	101.9	127.3	161.0	186.4	221.8	245.8	273.6	303.1	332.7
120			74.0	101.0	128.0	162.0	186.8	221.7	246.1	274.5	303.4	333.2
130			82.0	101.0	130.0	162.0	187.0	222.0	246.3	274.4	303.6	333.8
140			100.0	100.0	131.5	161.3	187.3	222.0	247.2	275.0	303.9	333.9
150					134.0	161.0	187.9	222.0	247.1	275.2	304.2	334.2
160					137.0	161.0	188.0	221.6	247.3	275.3	304.4	334.6
170					140.0	160.8	188.2	221.9	247.8	275.6	304.6	334.8
180					146.0	160.4	190.0	220.8	247.9	275.7	304.8	334.9
190					155.6	160.2	192.0	220.4	248.1	275.6	305.1	335.2
192					158.0	158.0						
200							196.0	220.0	248.2	275.9	305.2	335.7
210							200.0	218.0	248.8	275.8	306.3	336.8
220							207.0	216.0	249.0	275.9	306.9	337.2

S = Surge.
AT = Advance Time (minutes).
RT = Recession Time (minutes).

Data For Figure 11.

Table 23. - Advance and Recession Data for surge Flow of 2.5 lps Discharge and 120 minutes Cycle Time and 0.5 Cycle Ratio.

Distance	1st S		2nd S		3rd S		4th S	
(m)	AT	RT	AT	RT	AT	RT	AT	RT
00	00.0	65.0	120.0	18.0	240.0	300.0	860.0	420.0
10	01.2	67.0	120.6	181.0	240.1	300.1	360.1	420.1
20	02.0	68.0	121.0	182.0	240.3	300.2	360.2	420.3
30	04.0	70.0	121.4	283.4	240.4	306.6	350.3	420.4
40	06.1	71.0	121.8	185.8	240.5	300.7	360.9	422.5
50	10.0	72.3	122.0	187.0	240.6	300.8	361.2	423.7
60	13.5	74.0	122.0	188.0	240.7	301.2	362.2	423.6
70	19.1	75.0	122.3	189.0	241.2	301.4	363.3	423.9
80	24.0	76.0	123.0	189.6	241.3	301.8	364.9	424.2
90	30.0	77.0	124.0	190.0	241.4	301.8	365.8	425.6
100	37.9	77.9	125.0	190.0	241.6	302.0	366.5	426.5
110	45.0	76.0	127.0	190.0	242.0	302.8	367.4	427.0
120	56.0	75.8	128.0	190.0	242.1	302.9	368.8	427.1
126	78.0	74.0						
130			129.3	190.0	242.2	303.2	369.5	426.2
140			131.0	190.0	242.3	303.8	370.2	427.9
150			133.0	190.0	242.5	304.1	371.7	427.7
160			136.0	190.0	242.6	304.5	372.0	427.5
170			140.0	188.6	242.7	304.7	373.4	426.0
180			143.0	188.9	243.0	304.8	374.5	425.9
190			147.0	188.0	243.2	305.2	375.6	425.7
200			151.0	186.5	243.5	305.6	376.1	425.5
210			156.0	185.0	244.1	306.0	377.3	425.5
220			161.3	182.0	245.0	306.2	378.0	425.2

S - Surge.

AT = Advance Time (minutes).

RT = Recession Time (minutes).

Data For Figure 13.

Table 24.- Surface Runoff Hydrograph Data For Continuous and Surge Flow of 1.0 lps Runs.

Continuous Flow

TET (minutes)	FR (lps)
450	0.000
455	0.213
460	0.305
465	0.310
470	0.310
475	0.305
480	0.300
485	0.290
490	0.285
495	0.148
500	0.000

Surge Flow — (60/0.5) *

TET (minutes)	FR (lps)
1st Surge	
339	0.000
340	0.100
345	0.185
350	0.245
355	0.210
360	0.125
365	0.045
367	0.000
2nd SURGE	
376	0.000
380	0.195
385	0.405
390	0.530
395	0.610
400	0.618
405	0.452
408	0.000
3rd SURGE	
432	0.000
435	0.172
440	0.443
445	0.625
450	0.632
455	0.365
459	0.000

Surge Flow — (90/0.5) *

TET (minutes)	FR (lps)
1st Surge	
324	0.000
324	0.000
325	0.025
330	0.112
335	0.121
338	0.000
2nd SURGE	
375	0.000
380	0.425
385	0.650
390	0.671
395	0.612
400	0.283
405	0.052
406	0.000
3rd SURGE	
464	0.000
465	0.012
470	0.315
475	0.602
480	0.752
485	0.771
490	0.692
495	0.512
500	0.000

Surge Flow — (120/ 0.5) *

TET (minutes)	FR (lps)
1st Surge	
410	0.000
410	0.000
415	0.285
420	0.390
425	0.425
430	0.421
435	0.360
440	0.215
445	0.050
447	0.000
2nd SURGE	
495	0.000
500	0.352
505	0.585
510	0.600
515	0.612
520	0.615
525	0.620
530	0.625
535	0.620
540	0.452
545	0.321
550	0.000
3rd SURGE	
608	0.000
610	0.105
615	0.351
620	0.602
625	0.631
630	0.635
635	0.630
640	0.625
645	0.615
650	0.571
655	0.431
660	0.253
664	0.000

* = Cycle Time/ Cycle Ratio.
TET = Total Elapsed Time.
FR = Flow Rate.

Data For Figure 14.

Table 25.- Surface Runoff Hydrograph Data For Continuous and Surge Flow of 1.5 lps Runs.

Continuous Flow		Surge Flow (60/0.5)*		Surge Flow (90/0.5)*		Surge Flow (120/0.5)*	
TET (minutes)	FR (lps)	TET (minutes)	FR (lps)	TET (minutes)	FR (lps)	TET (minutes)	FR (lps)
395	0.000	1st SURGE		1st SURGE		1st SURGE	
400	0.321	346	0.000	299	0.000	292	0.000
405	0.485	350	0.135	300	0.051	295	0.152
410	0.510	355	0.120	305	0.372	300	0.305
415	0.515	356	0.000	310	0.531	305	0.361
420	0.515	2nd SURGE		315	0.552	310	0.385
425	0.515	371	0.000	320	0.560	315	0.361
430	0.510	375	0.350	325	0.500	320	0.223
435	0.451	380	0.800	330	0.222	324	0.000
440	0.000	385	0.815	334	0.000	2nd SURGE	
		390	0.830	2nd SURGE		374	0.000
		395	0.750	377	0.000	375	0.052
		396	0.000	380	0.181	380	0.452
		3rd SURGE		385	0.500	385	0.751
		428	0.000	390	0.765	390	0.805
		430	0.183	395	0.780	395	0.805
		435	0.702	400	0.785	400	0.800
		440	0.841	405	0.432	405	0.795
		445	0.850	409	0.000	410	0.789
		450	0.849	3rd SURGE		415	0.755
		455	0.621	464	0.000	420	0.670
		457	0.000	465	0.120	425	0.512
				470	0.492	426	0.000
				475	0.812	3rd SURGE	
				480	0.778	494	0.000
				485	0.752	495	0.552
				490	0.573	500	0.773
				495	0.321	505	0.810
				500	0.000	510	0.831
						515	0.855
						520	0.875
						525	0.900
						530	0.800
						335	0.700
						540	0.453
						544	0.000

* = Cycle Time/Cycle Ratio
TET = Total Elapsed Time.
FR = Flow Rate.

Data For Figure 15.

Table 26. -Surface Runoff Hydrograph
Data for Continuous and Surge
Flow of 2.0 lps Runs .

Continuous Flow		Surge Flow (60/0.5)*		Surge Flow (90/0.5)*		Surge Flow (120/0.5)*		Surge Flow (50/0.5)*	
TET (minutes)	FR (lps)	TET (minutes)	FR (lps)	TET (minutes)	FR (lps)	TET (minutes)	FR (lps)	TET (minutes)	FR (lps)
346	0.000	1st SURGE		1st SURGE		1st SURGE		1st Surge	
350	0.372	299	0.000	299	0.000	265	0.000	328	0.000
355	0.653	320	0.050	300	0.065	270	0.453	330	0.258
360	0.725	325	0.351	305	0.453	275	0.612	335	0.555
365	0.732	330	0.600	310	0.621	280	0.665	340	0.530
370	0.740	335	0.821	315	0.715	285	0.705	345	0.421
375	0.745	340	0.805	320	0.723	290	0.721	346	0.000
380	0.564	345	0.822	325	0.621	295	0.730	2nd SURGE	
385	0.121	350	0.815	330	0.483	300	0.730	364	0.000
386	0.000	355	0.653	334	0.000	305	0.710	365	0.211
		360	0.350	2nd SURGE		310	0.600	370	0.822
		365	0.000	376	0.000	315	0.405	375	1.155
		2nd SURGE		380	0.451	320	0.125	380	1.156
		374	0.000	385	0.823	321	0.000	365	0.732
		375	0.100	390	1.075	2nd SURGE		388	0.000
		380	0.562	395	1.122	373	0.000	3rd SURGE	
		385	1.000	400	1.130	375	0.212	411	0.000
		390	1.192	405	1.120	380	0.508	415	0.358
		395	1.175	410	0.953	385	0.745	420	0.856
		400	1.160	415	0.653	390	0.935	425	1.162
		405	0.700	418	0.000	395	1.028	430	0.706
		406	0.000	3rd SURGE		400	1.075	435	0.000
		3rd SURGE		456	0.000	405	1.055		
		422	0.000	460	0.355	410	0.985		
		425	0.300	465	0.953	415	0.852		
		430	0.692	470	1.152	420	0.521		
		435	1.000	475	1.175	423.9	0.000		
		440	1.183	480	1.200	3rd SURGE			
		445	1.122	485	1.195	490	0.000		
		450	1.199	490	1.153	495	0.509		
		455	1.192	495	0.856	500	0.782		
		460	0.862	500	0.563	505	1.021		
		465	0.325	503	0.000	510	1.130		
		466	0.000			515	1.155		
						520	1.175		
						525	1.180		
						530	1.190		
						535	1.165		
						540	0.872		
						541	0.000		

* = Cycle Time / Cycle Ratio
TET = Total Elapsed Time.
FR = Flow Rate.

Data For Figure 16.

Table 27. - Surface Runoff Hydrograph Data For Continuous and Surge Flow of 2.5 lps Runs.

Continuous Flow		Surge Flow					
		(60/0.5)*		(90/0.5)*		(120/0.5)*	
TET (minutes)	FR (lps)	TET (minutes)	FR (lps)	TET (minutes)	FR (lps)	TET (minutes)	FR (lps)
308	0.000	1st SURGE		1st SURGE		1st SURGE	
310	0.146	207	0.000	210	0.000	161	0.000
315	0.452	210	0.175	215	0.432	165	0.400
320	0.765	215	0.225	220	0.652	170	0.475
325	1.042	216	0.000	225	0.683	180	0.353
330	1.055	2nd SURGE		230	0.612	182	0.000
335	1.060	247	0.000	234	0.000	2nd SURGE	
340	1.065	250	0.321	2nd SURGE		231	0.000
345	1.065	255	0.834	276	0.000	235	0.325
350	1.060	260	1.132	280	0.532	240	0.826
355	1.055	265	1.150	285	0.921	245	1.123
360	1.041	270	1.144	290	1.100	250	1.305
365	1.000	275	0.453	295	1.183	255	1.352
370	0.748	276	0.000	300	1.213	260	1.385
375	0.352	3rd SURGE		305	1.245	265	1.380
380	0.000	306	0.000	310	1.250	270	1.371
		310	0.632	315	1.000	275	1.365
		315	1.156	320	0.100	280	1.350
		320	1.235	321	0.000	285	1.210
		325	1.240	3rd SURGE		290	1.060
		330	1.056	369	0.000	295	0.721
		333	0.000	370	0.125	300	0.253
				375	0.483	302	0.000
				380	0.859	3rd SURGE	
				385	1.153	366	0.000
				390	1.260	370	0.345
				395	1.320	375	0.859
				400	1.360	380	1.102
				405	0.800	385	1.357
				406	0.000	390	1.465
						395	1.472
						400	1.475
						405	1.456
						410	1.460
						415	1.100
						420	0.000

* = Cycle Time/ Cycle Ratio
TET = Total Elapsed Time.
FR = Flow Rate.

Data For Figure 17.

EVALUATION OF SURGE FLOW FURROW IRRIGATION IN THE JORDAN VALLEY

BY

MUHIB A. AL-AWWAD

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FACULTY OF AGRICULTURE

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