FACTORS WHICH AFFECT FURROW INTAKE RATES

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To apply irrigation water efficiently, the water must be absorbed evenly across the field. In surface irrigation systems, this requires either that the water be spread quickly across the soil surface so that each portion of the field has a nearly equal time to absorb water, and that all portions of the field absorb water at the same rate; or that water intake rate varies across the field to compensate for differences in intake opportunity time.

Water distribution in surface irrigation systems is determined by: 1) the water application system capabilities and management, and 2) the infiltration characteristics of the field soils. Improved application systems and design procedures for surface irrigation are being developed. But unless soil infiltration rates can be managed to achieve uniform water intake at desireable rates, high surface irrigation application efficiencies cannot be achieved. Although the problem of nonuniform soil water intake can be solved by applying the water through sprinkler or trickle systems at rates lower than the lowest intake rates, with the present high energy costs, this option is often not economical.

The objective of this study is to evaluate several farmer manageable factors which can affect water intake rates into irrigated furrows. The long term research goal is to quantify the effects of farmer practices which decrease intake uniformity, practices he can apply to improve uniformity, and practices which can change intake rates. Intake rate modification can be useful to accelerate advance (thus decreasing variations in intake opportunity times), counteract the effects of variations in intake opportunity times, or better adapt a field to a fixed or desireable water application system or schedule.

The manageable factors which will be discussed are:

1) wheel compaction of furrows
2) surface soil water content
3) flow rates, and
4) intermittant application, such as "surge" irrigation.

PROCEDURE

Field Studies

Several irrigation evaluations were carried out to quantify the effects of the listed factors on furrow intake rates. The field studies were conducted on three fields near Kimberly, Idaho. The Portneuf silt loam soils appeared uniform in the test areas. Field slopes were uniform on each field and ranged from .007 to .012 m/m. Run lengths ranged from 100 to 180 m. Reported results were on first irrigations of recently tilled land unless otherwise noted. Care was taken to prevent nonuniformity during tillage operations (i.e. all preplant operations were across the furrows). Table 1 describes

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Table 1. Summary Description of Field Study Sites, Conditions, & Treatments

Field/ Section No.	No. of Furrows Measured	Furrow Length (m)	Field Slope	Test No.	Soil Condition	Treatments
1-1	35	100	0.007	1	Initial irrigation on newly tilled soil	3 flow rates (8, 15 & 22 L/min) Surge and constant flow Wheel compaction
				2	Second irr. on fallow land	3 flow rates (8, 15 & 22 L/min) Surge and constant flow Wheel compaction
				3	Initial irrigation on newly tilled soil	Interrupted flow (60 min)
1-2	48	100	0.007	1	Existing & newly opened furrows in wheat stubble	3 flow rates (8, 15 & 22 L/min) Surge and constant flow Wheel compaction
				2	Initial irrigation on newly tilled soil	3 flow rates (8, 15 & 22 L/min) Surge and constant flow Moist (W=13%) & dry (W=5%) surface soil Wheel compaction
2-1	24	160	0.008	1	Initial irrigation on newly tilled soil	3 flow rates (17, 24 & 30 L/min) Surge and constant flow
				2	Second irr. on beans	3 flow rates (17, 24 & 30 L/min) Interrupted flow (40 min) Moist (W=13%) and dry (W=6%) surface soil
2-2	48	160	0.008	1	Second irr. on sugar beets	Interrupted flow (11 hrs)
3-1	30	180	0.012	1	Initial irrigation on newly tilled soil	3 flow rates (22, 26 & 32 L/min) Interrupted flow (70 min) Moist (W=11%) and dry (W=4%) surface soil

the various sites and test conditions.

Water was applied through orifices in level pipes in which a constant head was applied. Furrow inflows were checked volumetrically with a bucket and stopwatch. Intermediate and tail flows were measured with plastic 60^{o} V-notch flumes (ASAE, 1982) which had been volumetrically calibrated (Trout, 1983). Water advance fronts in each furrow were recorded at least four times during the advance phase or at the end of each surge. Surface soil moisture samples were collected from the surface 5 to 10 mm of selected furrows with a trowel and analyzed gravimetrically. Moisture contents are given on a dry weight basis. All comparative tests were carried out on the same or consecutive days so that subsurface soil moisture levels did not vary significantly between treatments.

Wheel compacted furrows were created by opening the furrow behind the tractor wheels (in the wheel tracks). Uncompacted furrows were opened between wheel tracks. All surge or intermittent flows were controlled manually.

Soil Column Studies

In order to verify some of the field findings under more controlled conditions, column infiltration studies were carried out. The soil columns were contained in 260 mm diameter, 550 mm long PVC cylinders. Air release holes were drilled in the sides and bottom of the cylinders. Water inlet and outlet taps were placed through the sides at the soil surface. Water was initially applied through both taps to minimize surface flow velocities. Ponded water depth was maintained at 20 mm with mariotte siphon supply reservoirs. Reservoir levels, and thus infiltrated volumes, were monitored with pressure transducers and logged by an automatic data logger.

Acrylic plastic paddles, consisting of four 5 mm thick vertical plates attached radially to a disk, were suspended over each column. The paddles were used to level the dry soil surface and then raised 6 mm and rotated at 15-18 rpm to cause water movement similar to that occuring in furrows. The paddles rotated the 20 mm of water ponded on the soil surface at up to 250 mm/sec at the outer perimeter.

The bottom 250 mm of the columns were filled with air dried soil (1 to 3 % moisture content) which had been passed through a 2 mm mesh screen and was packed to a density of 1.4 gm/cm^3 to simulate undisturbed soil below the tilled layer. Soil for the top 200 mm was air dried, passed through a 12 mm mesh screen and poured in loosely to represent a tilled layer. This layer was packed to a density of 1.26 gm/cm^3.

Aggregate Stability Determinations

To determine the effect of initial moisture content on the stability of aggregates and thus their tendency to break down and seal the furrow wetted perimeter, the aggregate stability of the Portneuf soil was measured under varying moisture conditions. Aggregates with diameters from 1 to 2 mm were moistened slowly by exposing them to water vapor until samples with water contents from 2 to 30 percent were obtained. Their stabilities were determined by placing them in a 50 mesh sieve, immersing the aggregates in water and sieving them gently for three minutes. The material retained on the sieve, other than coarse sands, was considered to be stable aggregates.

RESULTS

Wheel Compaction

The factor which caused the most change in water intake of the Portneuf silt loam soil was wheel compaction of the furrow. In newly tilled soil in which the tractor wheel packed the soil ahead of the furrow opener, the average advance time was 1/3 and steady state intake rate was 1/2 that in the untracked furrows. At the lowest tested inflow rate (8 L/min) only packed furrows completed the advance across 100 m long field #1. During the second irrigation on the same field without any additional traffic on the furrows, 80 percent of these differences in both advance times and infiltration rates still existed. This infiltration rate decrease is near the average of those reported by Kemper, et al. (1982) on the same soil type and is similar to that achieved (Bakhsh, et al. 1978) on a silt loam soil near Greeley, Colorado with a special furrow compactor.

On fields 2 and 3, furrows along the edges of the plot where the tractor had passed repeatedly while turning during cross-tillage operations were monitored and compared to the remaining furrows. The steady state intake rate on these more heavily trafficked areas was 20 percent less than in the remaining furrows. This difference continued in the second irrigation. Advance rates, however, were not faster in the compacted area, perhaps due to the fact that the final tillage pass before planting and furrowing loosened the top 5 cm of the soil surface.

Before plowing several sections of field #2 were purposely compacted before plowing with a truck filled with gravel to simulate the compaction caused by driving a loaded truck through a field during harvest. In these sections, advance rates were again unaffected, but intake rates were reduced. The effect of the below-plow-layer compaction increased over time, as would be expected, to a nearly 50 percent intake rate decrease at the end of a 12 hour irrigation.

Surface Soil Moisture

Disintegration of aggregates on the furrow wetted perimeter and the hydraulic repacking of the soil particles can eliminate the larger soil pores and form a surface seal which may reduce furrow intake. Therefore, the stability of the surface aggregates can be an important determinant of furrow intake rate. The aggregate stability of the Portneuf soil increases as the soil moisture content at the time of wetting increases (Fig. 1). This implies that the drier the soil surface at the time of irrigation, the greater the disintegration of the furrow surface aggregates, which would be expected to lower the furrow intake rate.

Three tests were carried out to determine whether this occurs in the field. The first compared an irrigation immediately after tillage and furrow forming while the soil surface was at 13 percent moisture content (by wt.), with an irrigation after one day of drying when the surface moisture was 5%. Subsoil moisture conditions were not significantly different. In the second and third studies parts of the fields were irrigated following gentle 1.5 mm rainfalls and the rest were irrigated the following day. The surface soil moisture contents were 11 percent and 13 percent, respectively, at the beginning of the first day irrigations, and 4 percent and 6 percent after one day's drying.

In the first test, (field 1-2, test 2) the advance rate averaged 40 percent greater and the intake rate 20 percent lower in the moister surface soil. In one of the tests following the trace of rainfall, (field 2-1, test 2) the water advanced 20 percent faster and infiltrated 20 percent slower in the moist soil than the drier soil. There was no significant difference of either the advance or intake rate in the third test.

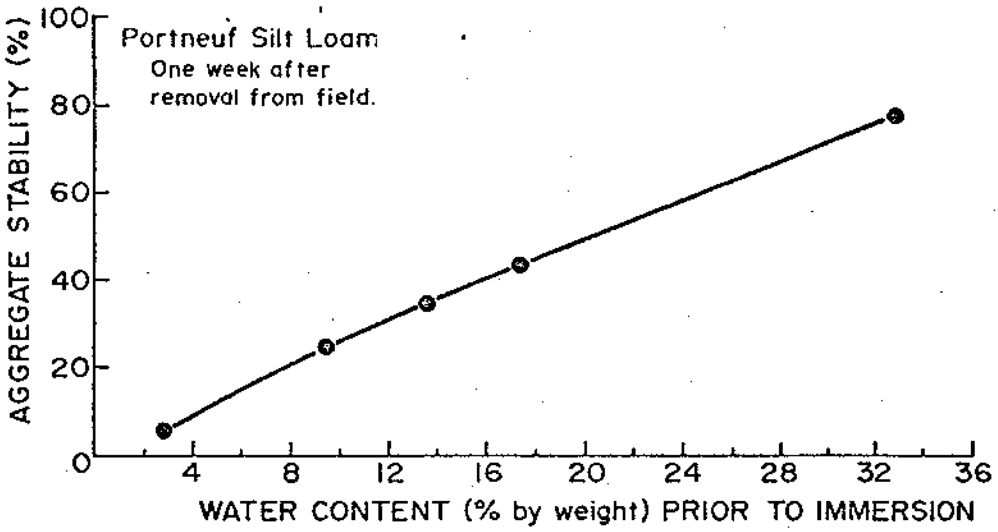

Fig. 1 Aggregate Stability (in Percent Retained on 50 Mesh Sieve) as Affected by Water Content Immediately Prior to Immersion.

Failure of the field intake rates to be higher when the soil surfaces were moist may be partially due to the reduced capillary suction of the moist soil or due to the cooling effect of the surface moisture on the soil and thus the water being infiltrated. Cooler water will have higher viscosity and tend to move through the soil more slowly. However, since the moisture difference was only in the surface 5 to 10 mm, these differences would be expected to be short term. They could account for the more rapid advance but not the difference in intake rates which persisted throughout the irrigations.

Several infiltration determinations in the soil columns in which 2 mm of water was gently sprayed on the soil surface 20 minutes before the initiation of the test, did not indicate any effect of the surface moisture on infiltration rates, either with or without stirring of the ponded water.

Stieb (1983) also reported no measureable effect of initial surface soil moisture on intake into the soil bed of a laboratory flume.

The lower stability of drier aggregates was not reflected in lower intake rates in these field or the soil column studies. This may be due to the fact that the initial products of breakdown of the aggregates is microaggregates less than 0.25 mm in diameter, with little or no dispersed clay size particles. Calculations indicate that pores between such microaggregates will still conduct water as fast as the observed intake rates. Apparently further breakdown of these microaggregates is required to appreciably decrease intake rates.

Flow Rates

Several authors report that the intake rate into a furrow will increase with flow rate due to increased wetted perimeter (Fangmeier and Ramsey, 1978) or water surface width (Merriam, 1980). Fangmeier and Ramsey (1978), using precision formed and monitored furrows, found that intake varies linearly with wetted perimeter. In typical furrows, the wetted perimeter increases about 1/4 to 1/3 as fast as the flow rate. Thus a measureable change in intake rate would be expected with a large enough (> 30%) change in the flow rate, and the intake rate into the lower end of a furrow, where much of the flow has been depleted by infiltration, should be significantly less than into the upper end.

On all of the evaluated fields three flow rates were used. On field 1-1, intake rates did vary significantly with inflow rate. Intake rates increased

10 to 25 percent with a 50 percent increase in furrow flow rate during the initial irrigation. The intake rate variation was only 10 percent with the same inflows during the second irrigation. In all other tests, no consistant variation in intake rate with flow rate could be measured when inflows were varied ± 50 percent between furrows or ± 20 percent over time within a furrow.

Flow measurements at midfield allowed calculation of intake rates into the upper and lower halves of the fields. In both tests on field 1-1, the intake into the bottom half of the furrow, where the average flow rate was about half the average flow rate in the top section, was 15 to 30 percent less than into the top section. On field 2-1, intake rates were higher into the lower section of the furrows. On the third field, intake rates were about the same in the upper and lower sections.

One possible reason for the higher than expected intake into the lower half of the furrow or in furrows with lower inflow rates is that, due to the slower advance rate, the furrow surface soils will be wet up more slowly, the aggregates will tend to disintegrate less, and larger pores will be maintained (Kemper et al. 1975). However, laboratory tests on this soil did not demonstrate increased infiltration rates at slower rates of wetting in either stirred or unstirred soil columns. Another possible reason is that the higher flow velocities associated with the higher flow rates create larger shear forces on the soil surface and more bed load movement causing greater disintegration of the aggregates and hydraulic rearrangement of the primary particles into denser configurations. This could result in less permeable surfaces. Steib (1983) found that surface sealing increases with flow velocity.

Intermittent Application

Intermittent application of water to furrows, also termed surge irrigation, has been demonstrated to increase water advance rates (Bishop, et al. 1981) and reduce infiltration rates (Walker, et al 1982) in some soils.

Surge application was included as a treatment in five of the furrow irrigation tests. Surge cycles of initially 30 minutes and later 60 minutes duration with 50 percent off time were continued for at least 3 cycles until advance was complete. The surging reduced advance times compared to constant inflow furrows (counting only inflow time) 15 to 40 percent at medium flow rates (see Table 1). At 50 percent higher flow rates surge sometimes decreased the advance times as much as 15 percent but often increased the advance time if the constant inflow advance was rapid. At the low inflow rates, surging sometimes allowed water to reach the end of furrows in which the advance otherwise would not be complete. The variability in the advance times within treatments was too large to allow a quantitative prediction of surge effects on advance rates.

Repeated interruptions of water supply to the furrows as in normal surge irrigation tended to lower furrow intake rates by 20 to 30 percent. Independent blocked furrow infiltration measurements (Walker, et al. 1982) on one of the test fields by personnel from the Agricultural and Irrigation Engineering Department of Utah State University indicated a 33 percent decrease in intake rates with surging. The larger decrease may have been due to disintegration of aggregates by the impeller of the pump used to circulate the water and sediment. In most cases, the intake rate on the surged furrows remained lower than in constant flow furrows for several hours after the surging ceased although the magnitude of the reduction declined with time.

Intermittent ponding was applied to soil columns by closing the water inlet and draining the ponded water through an outlet tap into a bottle from which it was later reapplied. Intermittent ponding consistently reduced soil intake rates in stirred columns by 20 to 30 percent compared to constant application at the same ponded times or infiltrated depths. In unstirred columns, the decrease was only half as large.

The furrow intake rate of the silt loam soils in southern Idaho decreases during the first hour or two of water application to a fairly steady rate. Then, 2 to 3 hours after wetting, furrows begin to take in water more rapidly as shown in Figure 2. The cause of this phenomena has not yet been determined but may relate to the breaking up and eroding away of a surface seal layer, to the emergence of "macropores" such as earthworm holes on the furrow wetted perimeter, or to increased soil porosity due to swelling.

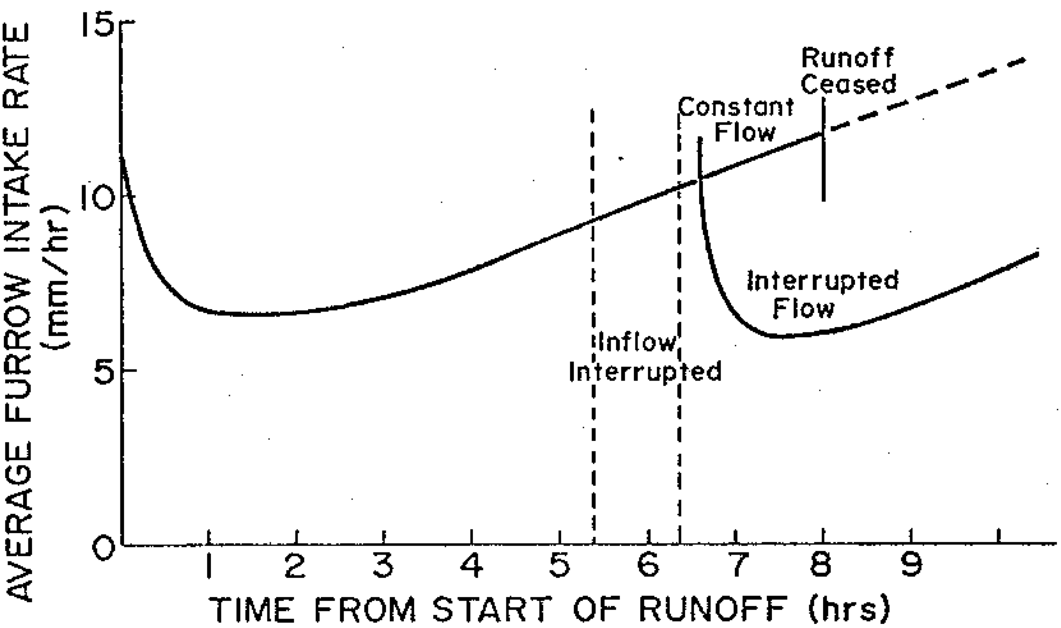

Fig. 2 Typical Average Furrow Intake Rate Over its Full Length as Measured by Inflows and Outflows with Constant and Interrupted Inflows on Portneuf Soil.

Due to this increased intake rate, if the water advance is not completed in the initial 2 to 3 hours it usually will never reach the lower end of the furrow. In furrows in which the advance has reached the end of the furrow, runoff commonly decreases with time and often begins to recede from the lower end inspite of continued steady inflows. This "backing up" of the water from the lower end of furrows is a major problem for area farmers and forces them to use higher inflow rates, resulting in high erosion and tail water runoff early in the irrigation.

A different type of intermittent application was tested on all three fields to combat this problem. Water was applied at a constant rate for the first 4 to 8 hours of an irrigation. When intake rates increased and tail water outflows decreased or stopped, the inflow was shut off. The time for which furrow supply was stopped varied from 40 minutes to overnight. When water was reintroduced at the same rate into the furrow, it advanced to the tail quickly (20-40% of the initial advance time) and intake rates were reduced. In three field tests the average intake rates were initially reduced 20 to 50 percent below the pre-flow interruption value and runoff rates returned to near their peak values as illustrated in Fig. 2. Generally, intake rates were reduce most by the flow interruption in the furrows with the highest intake rates. The effect of the flow interruption continued unabated in field 1 where intake rates with steady inflow were fairly constant, but intake rates began again to slowly increase in the other tests at about the application time.

The reduced intake rates after interruption of the flow may be due to a consolidation of the wetted perimeter soils. Soon after the free water surface receeds from a furrow, the soils begin to consolidate due to the increasing soil water tension. Soil cracking is evidence of this consolidation. When water is reintroduced into the furrow, the cracks are quickly filled with sediment. The resulting wetted perimeter soil is more dense. Significantly smaller and fewer cracks observed in dried furrows where flows had been intermittent are evidence of this greater density. In the intermittently ponded soil columns, the density of the surface 3 cm of soil the day following the test tended to be slightly less and averaged 2 percent less than the soils under constant ponding.

DISCUSSION

Of the factors measured which affect furrow intake rates, the most important is wheel compaction of the irrigated furrow. The amount of intake decrease from compaction will depend upon the soil, the soil moisture at the time compaction, the average compactive force the wheel applies, and the soil surface or furrow shape relative to the wheel shape and width. Further studies are underway to evaluate these factors.

Some farmers carefully manage their cultivation and irrigation operations so that they irrigate only wheel compacted or uncompacted furrows. Others randomly irrigate wheel compacted and uncompacted furrows without regulating inflow rates for the variability in intake rates, which usually results in high runoff from compacted furrows. The type of tractor and size of planting and cultivation equipment the farmer uses can limit his ability to irrigate only wheel compacted furrows and gain the benefit of the resulting reduced intake rate (faster advance or smaller less erosive inflows). Figure 3 illustrates this problem.

For instance, if a farmer irrigates alternate furrows, his tractor has four wheels and he cultivates 4 rows as illustrated schematically in Fig. 3A, he has flexibility to irrigate either wheel or non-wheel furrows. In that figure the lines represent crop rows, the "V" represents cultivation tools whose points indicate the direction of tractor travel and the centers of furrows and the wavy lines represent water carrying furrows. He also has this flexibility if he irrigates every other furrow, has a three wheel tractor, and cultivates six rows per pass as indicated in Fig. 3B. However, if he has a four wheel tractor and cultivates 6,8 or 10 furrows per pass (i.e. Fig. 3C) he can only irrigate in non-wheel furrows to avoid the intake heterogeneity inherent in irrigation of both wheel compacted and uncompacted furrows. In any of the cases, if water is applied between all crop rows, this heterogeneity can't be avoided.

Special furrow packing wheels (Bakhsh, et al. 1978), which a few farmers use, can alleviate at least part of this problem and lead to more uniform water application with lower inflow rates.

Avoidance of cultivation and wheel track patterns which force farmers to the resulting intake heterogeneity should be a major criterion in a farmer's decisions concerning which equipment to buy and in the design of equipment by manufacturers.

These data also indicate that equipment passes during tillage operations before planting and even during the previous harvest can reduce intake rates. This implies that tillage operations which run parallel to the furrows can create intake non-uniformities among furrows, and that repeatedly tracked areas, such as turning areas and areas where trucks drive while hauling out a harvest

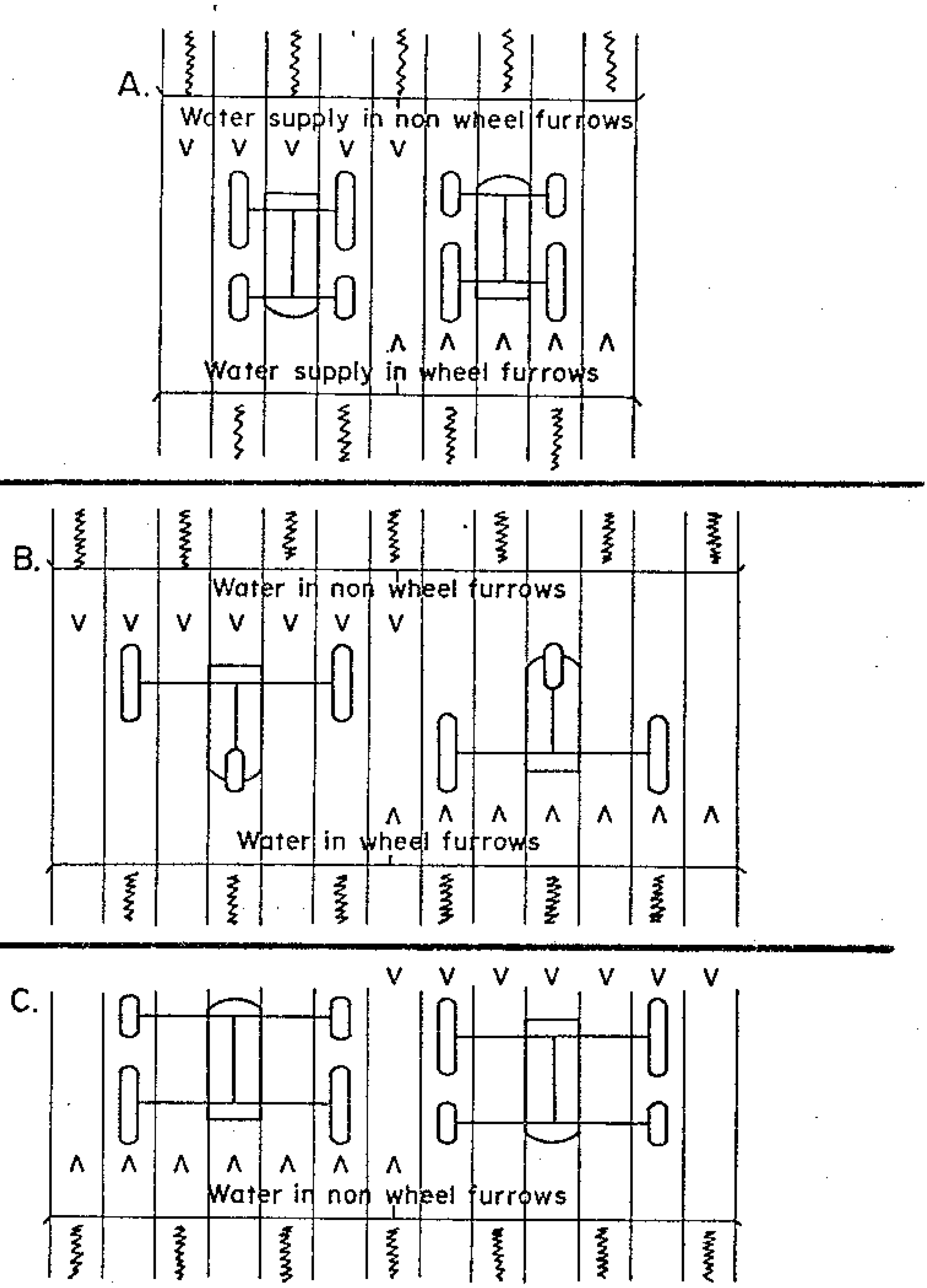

Fig. 3 Tractor Wheel and Furrow Water Supply Patterns Where Every Second Furrow is to be Irrigated.

will take in less water. Farmers striving for uniform water applications must be concerned during tillage with more than the visible appearance of the soil surface.

These studies indicate the affect of surface soil moisture on intake rates in the Portneuf soil is not yet fully understood. Although initial water content was found to affect aggregate stability, it either doesn't affect it enough to prevent aggregate disintegration on the surface of furrows, or the resulting microaggregates are still large enough that they don't form a seal which limits intake.

Likewise, these results show an inconsistent relationship between flow rate and intake rate. If the relationship is weak, as suggested, widely varying inflow rates will affect runoff amounts but not water distribution, and high runoff rates are not necessary to maintain reasonable intake into the lower ends of furrows. Further work is needed to verify this finding.

The factor which has been considered to affect furrow intake is not flow rate but wetted perimeter or furrow wetted width. In channels such as irrigation furrows, cross-sectional shape and thus wetted perimeter and width will vary with soil erosion and sediment accumulation. In the erosive Portneuf soils, changes in furrow slope not only affect flow depths, but also affect sediment movement and thus furrow shape. Where slopes increase, erosion creates deep narrow channels. Where slopes decrease, sediment deposits, cross sections are wide and wetted perimeters are large. Visual observations of soil surface wetting in fields with varying slopes indicate wide variations in water uptake.

These studies corroborate the previously measured effect of intermittent water application on intake rates. Surge flow can reduce advance times and improve application uniformities in soil with high initial intake rates. In soils, such as those tested, where intake rates, following an initial decrease, increase over time, interrupted flow can decrease intake rates to prevent bottom end recessions. Such interrupted applications should be studied further to determine the length and timing of interruption required to gain maximum effectiveness.

On field where soils appeared uniform, preplant tillage operations were across furrows, furrows were equally compacted, slopes were uniform, surface and subsurface moisture was uniform, and the irrigation was carried out at the same time with the same water supply, the variability of intake among furrows or between the top and bottom sections of furrows was still large. Standard deviations of individual furrow intake values were usually 20 to 30 percent of the mean, implying that a third of the furrows were absorbing at least 20 to 30 percent more or less water than the average application. (HSPA uniformity coefficient (UCH) = .76 to .84).

This variability in water application is of the same order as that produced by stationary sprinklers. However, it has the disadvantage in furrow irrigation of requiring a water supply rate to the furrows that is at least 25 percent greater than that which will be absorbed by the average furrow to assure that most furrows are wetted to their ends. Although farmers can adjust supply rates to individual furrows to minimize runoff, when water is plentiful and labor is scarce, runoff rates varying from 50 to 100 percent of intake rates are common. While this runoff is often returned to the distribution system and reused, it generally precludes use of surface irrigation water as a distributor of fertilizers, herbicides etc. unless runoff is reused. Consequently further efforts to reduce that heterogeneity are needed.

SUMMARY AND CONCLUSIONS

Tractor wheel compaction of furrows in Portneuf silt loam soils reduced their steady intake rate about 50 percent. Irrigating both compacted and uncompacted furrows thus caused significant heterogeneity of water infiltration. Nonuniform compaction during preplant tillage operations also affected intake rates, but to a lesser degree.

Compaction by wheels of tractors during cultivation operations is such a major factor causing heterogeneity of intake that tractors should be selected (or designed) to facilitate cultivation wheel compaction patterns so farmers can irrigate either in wheel compacted furrows or in furrows which have not been compacted.

Although soil water content prior to wetting affects the stability of aggregates, it did not significantly affect furrow intake rates in these soils.

Although wetted perimeter has been linearly related to furrow intake, the measured relationship between flow rate and intake was inconsistent. The lower ends of furrows where flow rates are reduced, did not generally infiltrate less water than upper sections.

Intermittent application reduces intake rates by 20 to 40 percent. Surging can extend advance in the furrows. A later flow interruption can prevent bottom-end recession during an irrigation.

With all these factors held constant, water intake into furrows on uniformly sloped fields with uniform appearing surface soils still has a substantial coefficient of variation ($\sigma/\bar{x} \approx .25$). Further studies are needed to identify the source of this variability and reduce it to a minimum.

REFERENCES

1. American Society of Agricultural Engineers. 1982. ASAE Standard S359.1: Trapezoidal flumes for irrigation flow measurement. Agricultural Eng. Yearbook 1982-83. St. Joseph, MI. pp. 542-544.

2. Bakhsh, Hazoor, Muhammad Khalid, and James L. Smith. 1978. Impact and wheel compaction of irrigated furrows. Paper No. 78-1534. Presented at the 1978 Winter Meeting of the American Society of Agricultural Engr. New Orleans, LA.

3. Bishop, A. Alvin, Wynn R. Walker, Niel L. Allen, and Gregory J. Poole. 1981. Furrow advance rates under surge flow systems. Journal of the Irrigation and Drainage Division. Proceeding of the American Soc. of Civil Engs. Vol 107, No. IR3. pp. 257-264.

4. Fangmeier, D. D. , and M. K. Ramsey. 1978. Intake characteristics of irrigated furrows. Transactions of ASAE 21-4. pp. 696-700.

5. Kemper, W. D. , John S. Olsen and Alan Hodgdon. 1975. Irrigation method as a determinant of large pore persistence and crust strength of cultivated soils. Soil Sci. Soc. of America Proc. Vol. 39, No. 3 pp. 519-523.

6. Kemper, W. D., B. J. Ruffing and J. A. Bondurant. 1982. Furrow intake rates and water management. Transactions of ASAE 25-2. pp. 333-339 and 343.

7. Merriam, John L. 1980. Use of the advance ratio for furrow irrigation design. Paper No. 80-2076. Presented at the 1980 Summer Meeting of The American Society of Agricultural Engr. San Antonio, Texas.

8. Steib, David J. 1983. Surface seal development with shallow overland flow. Masters Thesis submitted to Colorado State University, Ft. Collins, Colorado 80523.

9. Trout, Tom. 1983. Recalibration of the powlus fiberglass v-notch furrow flume. Unpublished report to the manufacturer. 11 p.

10. Walker, Wynn R., Hector Malano and John A. Replogle. 1982. Reduction in infiltration rates due to intermittent wetting. Paper No. 82-2029. Presented at the 1982 Summer Meeting of the American Soc. of Agricultural Engr. 14 p.