MONTANA STATE UNIVERSITY

# Water relations in highly calcareous very gravelly soils

by Daniel Lyle McLean

A thesis submitted in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE in Soil Science
Montana State University
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Abstract:

This study was undertaken because of the many irrigated acres of highly calcareous very gravelly soils in Western Montana and the uncertainties of permeabilities and available water capacities associated with them. Infiltration rates were recorded on large 9.3 square meter (100 square foot) plots in July 1975. Soil water was determined gravimetrically 2.5, 5, 9, and 16 days after saturation.

The substratum of these soils contains 80 percent (by weight) rock fragments so samples for moisture were taken by excavation with a backhoe. Bulk density for soil horizons containing a large amount of rock fragments was determined by a sand-fill excavation method.

Saturated hydraulic conductivity was 2.5 to 3.5 centimeters per hour. The "field moisture capacity" available for plant use was 13.5 centimeters for the Gravel soil and 19.3 centimeters for the Musselshell soil. Although the surface was covered to prevent evapotranspir-ation, these very gravelly soils continued to lose significant amounts of gravitational water for 16 days after saturation. If plants were allowed to use the free water during this period, very little gravitational water may have been lost after the first three days.

The data in this study can be used to properly design irrigation systems and determine irrigation frequencies for the Crave] and Musselshell soils. It can also be extrapolated to other highly calcareous very gravelly soils with similar characteristics.

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Date May 24, 1978

# WATER RELATIONS IN HIGHLY CALCAREOUS VERY GRAVELLY SOILS

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DANIEL LYLE MC LEAN

A thesis submitted in partial fulfillment
of the requirements for the degree

of

MASTER OF SCIENCE

in

Soil Science

Approved:

G.A. Nielsen
Chairperson, Examining Committee

Hayden Ferguson
Head, Major Department

Henry L Parsons
Graduate Dean

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# ABSTRACT

This study was undertaken because of the many irrigated acres of highly calcareous very gravelly soils in Western Montana and the uncertainties of permeabilities and available water capacities associated with them. Infiltration rates were recorded on large 9.3 square meter (100 square foot) plots in July 1975. Soil water was determined gravimetrically 2.5, 5, 9, and 16 days after saturation.

The substratum of these soils contains 80 percent (by weight) rock fragments so samples for moisture were taken by excavation with a backhoe. Bulk density for soil horizons containing a large amount of rock fragments was determined by a sand-fill excavation method.

Saturated hydraulic conductivity was 2.5 to 3.5 centimeters per hour. The "field moisture capacity" available for plant use was 13.5 centimeters for the Cravel soil and 19.3 centimeters for the Musselshell soil. Although the surface was covered to prevent evapotranspiration, these very gravelly soils continued to lose significant amounts of gravitational water for 16 days after saturation. If plants were allowed to use the free water during this period, very little gravitational water may have been lost after the first three days.

The data in this study can be used to properly design irrigation systems and determine irrigation frequencies for the Cravel and Musselshell soils. It can also be extrapolated to other highly calcareous very gravelly soils with similar characteristics.

# INTRODUCTION

A high calcium carbonate content and an abundance of rock fragments are two outstanding characteristics of soils in the dry intermountain valleys of Madison County, Montana. The significance of these characteristics on soil water relations are not fully recognized.

There is an abundance of high quality irrigation water in Madison County, as there is in most of the mountainous areas of Western Montana. Therefore, one of the most common requests was an on-site soil investigation for sprinkler irrigation design. Available water capacity and permeability or intake rate are of primary importance in this type of investigation.

Immediately a controversy was evident in the interpretation of S. C. S. technical guides for Borollic Calciorthids, loamy-skeletal, carbonatic soils. One interpretation was that very gravelly soils commonly have moderate to rapid permeability and calcium carbonate does not expand when wet, so it should have little effect on the permeability. The contradictory interpretation was that carbonates precipitate in soil pores, plugging them and leaving less pore space for movement of water, thus the permeability should be slow or very slow.

The percent clay in a soil is commonly used as an indicator to approximate available water capacity. However, this is not possible with highly calcareous soils because carbonates of clay size are not considered to be clay and are treated as silt (Soil Survey Staff 1975).

These conflicts and the questionable potential of these soils for irrigation aroused my interest, so I did some laboratory research on the calcic horizon of a Musselshell loam with about 65 percent carbonates. I determined saturated hydraulic conductivity on the less than 2 millimeter disturbed soil, bulk density on undisturbed peds and particle size analysis. The initial rate of flow on three replications in the lab was about 1.0 centimeter per hour, but after four days, they began to stabilize at about 0.5 centimeters per hour (Appendix 3). Gile (1961) made field observations and measurements of resistance to water infiltration in calcic horizons. Statistical analysis revealed a highly significant correlation between carbonate content and infiltration rate. As the carbonate content increased linearly, the infiltration rate decreased exponentially. The slow or moderately slow permeability of the disturbed sample in the lab was in conflict with field trials, so additional research was needed.

The solutions of many problems associated with soil-water flow depends upon knowledge of the hydraulic conductivity. Of the numerous methods which have been proposed for the measurement of hydraulic conductivity, Klute (1972) states the in situ methods must be regarded as preferable, because they are more directly applicable to the solution of the field problems.

Because of the difficulty of working with these soils, little or no work had been done with regard to rate of permeability or waterholding capacity of highly calcareous very gravelly soils. Infiltration rings are hard to install and seal in very gravelly soils. Likewise, the common methods of monitoring soil water are very difficult if not impossible to install in very gravelly soils.

The purpose of this study was to provide some benchmark data on the permeability and available water capacity of two highly calcareous very gravelly soils. This information could be expanded to some 25,000,000 acres in Western Montana alone (Southard 1969). Many of the soils in the western United States contain horizons of calcium carbonate accumulation, therefore, it is possible this information could be usefully extrapolated to other areas.

# LITERATURE REVIEW

The boundary of soils containing horizons of carbonate accumulation in the United States is a transect which runs approximately through the middle of Texas and north along the eastern border of North and South Dakota. In the extreme northern United States, this transect corresponds with about 50 centimeters (20 inches) mean annual precipitation and 5°C (42°F) mean annual temperature, whereas, in southern Texas it corresponds with about 60 centimeters (24 inches) mean annual precipitation and 22°C (72°F) mean annual temperature. This climatic relationship also appears in mountains and intermountain valleys where marked differences in climates and soil occur. Nearly every mountain-basin transect is characterized by a relatively warm-dry climate in the basins. Under appropriate conditions, therefore, soils on the lower slopes of the mountains and in the basins will contain $CaCO_3$ (Birkland, 1974; Lane et al. 1966; and Leet et al. 1965).

The concept of calcification has been revised with time just as the concepts of soil classification have been revised. Calcification, as defined by Kellogg in 1941, was a general term for those processes of soil formation in which the surface soil was kept supplied by the plants with enough calcium to prevent the soil from becoming acid and the colloids from leaching out (Jenny 1941). A more recent concept defines calcification as processes including accumulation of calcium carbonate in Cca and possibly other horizons of the soil (Buol et al. 1973).

There are other common carbonate minerals which occur in combination with calcium carbonate in soils, but carbonates of calcium are by far the most abundant carbonates in nature (Krauskopf 1967).

Soils in semiarid and arid regions commonly have a zone or horizon of secondary calcium carbonate accumulation. Many of these soils form prominent layers in which the morphology is determined by the impregnated carbonates. If the climate is dry enough or the surface erosion intense enough, these horizons may extend to the surface as they do in some areas of Madison County.

The origin of carbonate horizons involves carbonate-bicarbonate equilibria according to the following reaction:

$$\begin{tikzcd} & \mathrm{CO_2 + H_2O} \arrow[d, shift right] & \\ \mathrm{CaCO_3 +} & \mathrm{H_2CO_3} \arrow[u, shift right] \arrow[r, shift left] & \mathrm{Ca^{++} + 2HCO_3^-} \arrow[l, shift left] \end{tikzcd}$$

Any process that increases the amount of $CO_2$ available to the solution makes more $CaCO_3$ dissolve; anything that decreases the amount of $CO_2$ causes $CaCO_3$ to precipitate. At low pH, where most dissolved carbonates exist as $H_2CO_3$, the forward reaction is favored. At high pH the reverse reaction causes precipitation of $CaCO_3$. Dissolution is also favored by increasing the amount of water moving through the soil; however, precipitation takes place when ion concentration is increased to the point of saturation. Temperature also affects $CaCO_3$ equilibria. The solubility of $CaCO_3$ in pure water decreases as the temperature rises. This is opposite to the behavior of most salts where the general result of increasing temperature is to give high solubilities. In addition to this effect, the solubility of $CaCO_3$ in water decreases at higher temperatures because $CO_2$ is less soluble in hot water than in cold water. Although, both factors are involved, the solubility of carbonates is generally much more influenced by the change in solubility of $CO_2$ than by the temperature coefficient of the solubility of $CaCO_3$ (Birkeland 1974 and Krauskopf 1967).

The above conditions all occur in soils in which calcium carbonate has accumulated. Carbon dioxide produced by plant roots, microorganism respiration, and organic matter decomposition result in $CO_2$ partial pressures in soil air of 10 to more than 100 times that in the atmosphere (Birkeland 1974 and Buckman et al. 1969). This abundance of $CO_2$ decreases the pH which causes an increase in the solubility of $CaCO_3$. Thus, one would expect optimum conditions for dissolution of $CaCO_3$ in the A horizon and the amount of water leaching through the soil near the surface is also much greater than at depth. Calcification could occur as $CaCO_3$ is precipitated by a combination of decreasing $CO_2$ partial pressure below the zone of rooting and major biological activity, and the progressive increase in concentration with depth in $Ca^{++}$ and $HCO_3^-$ in the soil solution as water is lost by evapotranspiration.

# PROCEDURES

Sites were selected on the Jack Creek Bench east of Ennis, Montana (Figure 1). These sites were chosen because the two soils of major interest in this study occur in complex in this area, and previous laboratory tests had been done on the calcic horizon of one of these soils. Sites were in native range and on nearly level topography (Figure 2).

A 3 meter square (10 foot square) pond was constructed out of 2.5 centimeter by 25 centimeter (1 inch by 10 inch) boards so the surface area inside the pond was 9.3 square meters (100 square feet). Large ponds were used to better represent the common variations that occur in any soil surface. A narrow trench about 5 centimeters (2 inches) deep was dug in a 3 meter (10 foot) square. The boards were placed on edge in the trench, the ends sealed with caulking compound and nailed securely (Figure 3). Wooden stakes were driven around the outside of the pond for support and the loose soil that had been taken from the trench was tamped around the edges to prevent water leaks (Figure 3).

The 3 meter (10 foot) square ponds were used as buffer ponds and infiltration rings were placed inside them (Figure 4). Periodic readings of the water level in both the rings and the ponds were recorded using equipment and

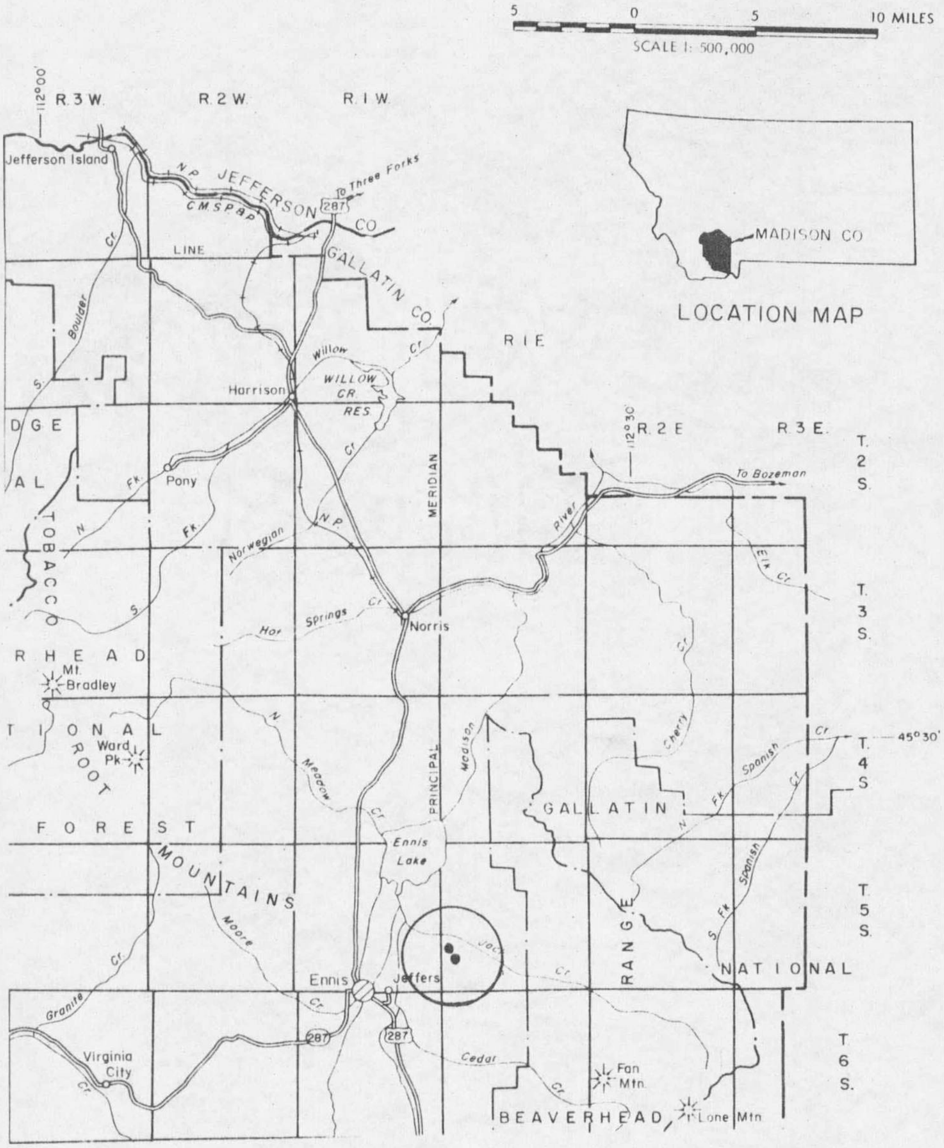

Figure 1 - Location of research plots on the Jumping Horse Ranch east of Ennis, Montana. The site location of the Cravel soil is approximately 402 meters south and 579 meters east of the northwest corner of section 30,T5S, R1E. The site location of the Musselshell soil is approximately 548 meters north and 610 meters west of the southeast corner of section 30, T5S, R1E.

Figure 2 - Site location on Jack Creek Bench east of Ennis, Montana, in native range on nearly level topography.

Figure 3 - Large buffer ponds constructed of wood and sealed to prevent leakage.

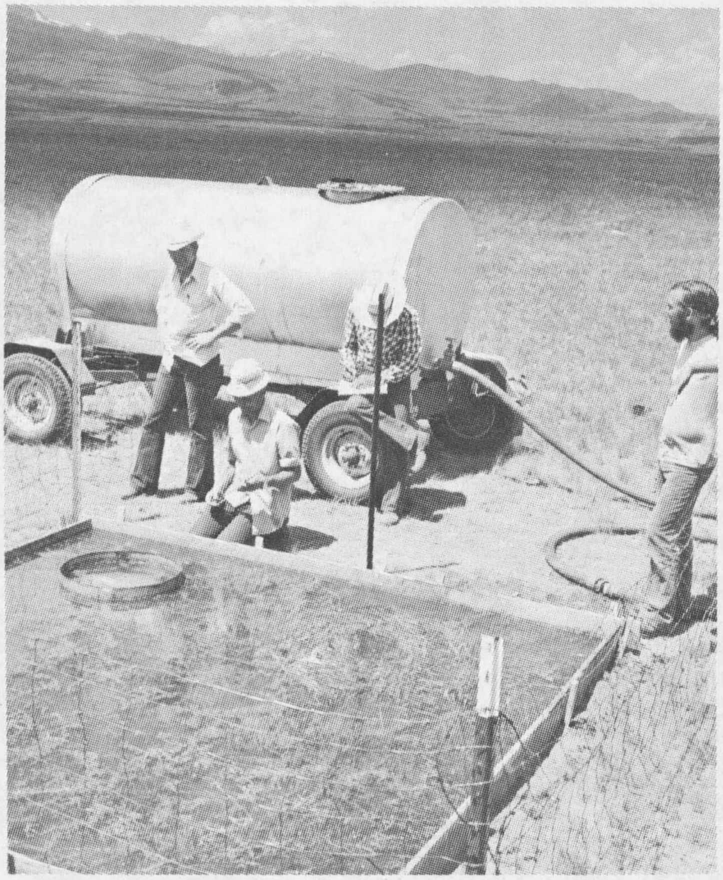

Figure 4 - Large buffer pond containing infiltration ring.

procedures of Haise et al. (1956) (Figure 5).

To duplicate quality of water available for irrigation, water was taken from a nearby irrigation ditch and hauled to the site with a 3,784 liter (1,000 gallon) water tank. A head of water was maintained on the plots for 8 to 12 hours and 30 centimeters to 38 centimeters (12 inches to 15 inches) total water infiltrated into the soil. A sheet of heavy (4 mil) black plastic was placed over each plot to prevent water loss by evapotranspiration.

After three days, one corner of each plot was excavated with a backhoe and soil samples put in small metal cans and sealed for water content determination. Depths sampled were 0-10cm, 20-35cm, 35-55cm, 55-80cm, 80-110cm, 110-141cm, and 141-152cm (Figure 6).

Samples were taken and the soil replaced in the pit as rapidly as possible to prevent water loss by evaporation. The samples were taken immediately back to Ennis, weighed, oven dried at 105$^{o}$C for 24 hours, and reweighed to determine water loss. The dried samples were dry sieved to remove the greater than 2 millimeter fraction. This coarse fraction was weighed and percent of sample was calculated.

Additional samples were collected in the same manner 5, 9, and 16 days after the initial saturation in the re-

Figure 5 - Hook gage used to measure water level.

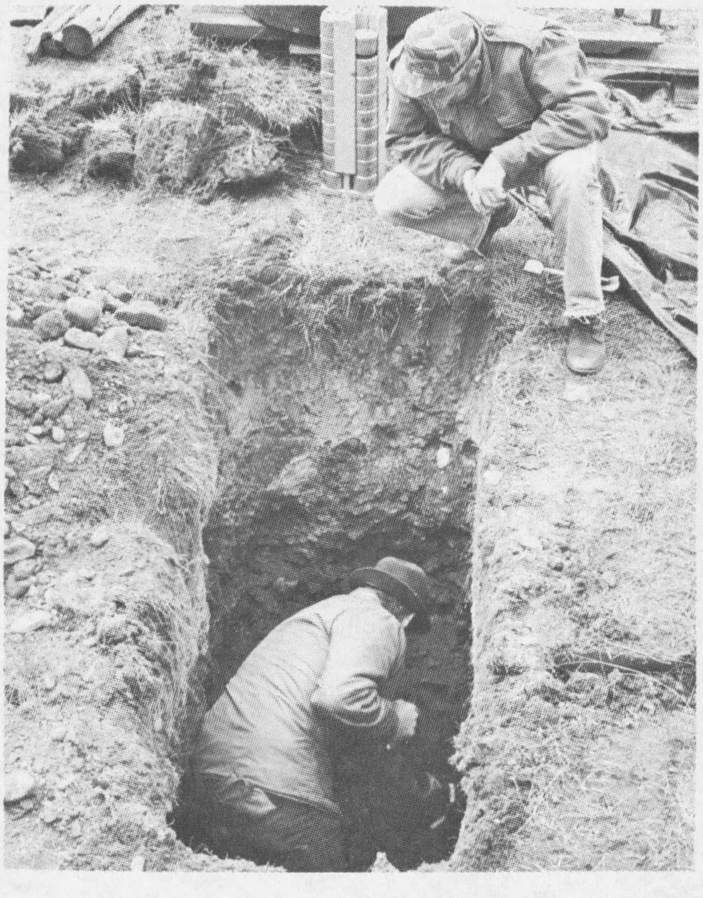

Figure 6 - Collection of soil water samples from excavated pits.

maining corners of the plots (Figure 7).

Profile descriptions were prepared using standard nomenclature (Soil Survey Staff 1951). Large samples were taken from horizons containing appreciable coarse fragments, to determine amount of coarse fragments and bulk density. Volume of excavated soil was determined by the sand-fill method of Blake (1965). Briefly this consisted of excavating about 1 kilogram of soil and coarse fragments in a cup-shaped hole. The hole was filled with dry sand with a predetermined settled density. A knife blade was inserted into the sand several times to allow settling. The sand was leveled to full and the volume of sand recorded. Bulk samples were put in bags and dried to determine dry weight. The bulk samples were then dry sieved to determine the greater than 2 millimeter coarse fraction.

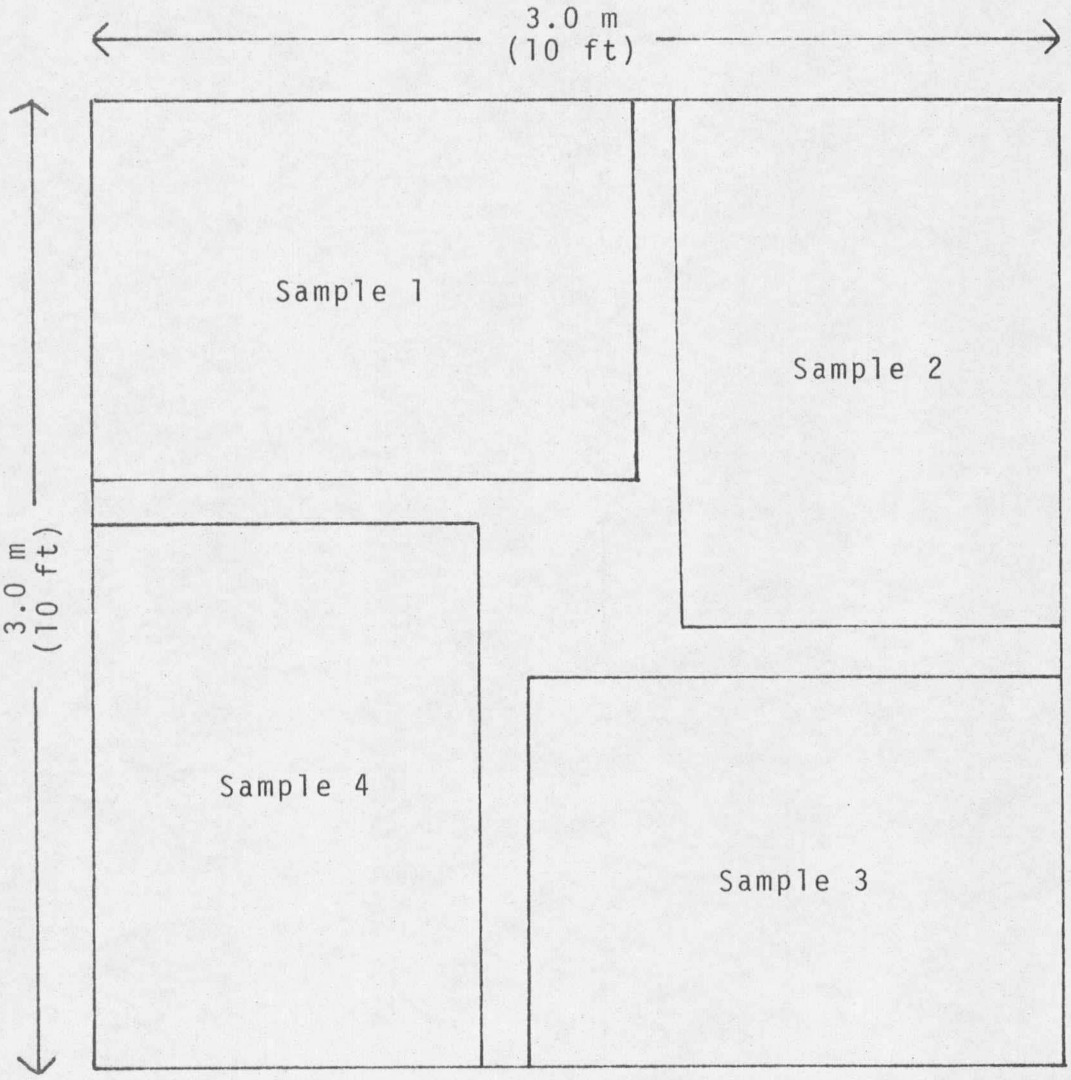

Figure 7 - Sample pattern within each plot. Sample 1 was collected 2.5 days after saturation. Sample 2 was collected 5 days after saturation. Sample 3 was collected 9 days after saturation. Sample 4 was collected 16 days after saturation.

# RESULTS AND DISCUSSION

Tables 1 and 2 give the main morphological characteristics of the soils at the two sites. These soils are representative of the two major highly calcareous soils in Madison County.

## Saturated Hydraulic Conductivity (Appendix 1)

Although the initial intake rates were quite rapid and variable, they stabilized well after three hours of continuous flow. The erratic flow rates measured in the ring during the first half-hour on the Musselshell plot prompted us to put another ring in the opposite end of the pond and record intake rates in it as well. After approximately five hours, both rings and the pond on the Musselshell plot had intake rates of 3.3 centimeters (1.30 inches) per hour. The intake rate in the ring in the Cravel plot stabilized at about 2.5 centimeters (1.0 inches) per hour, whereas the pond was near 3.5 centimeters (1.40 inches) per hour. Each profile received 30 centimeters (12 inches) or more total water over an 8 to 12 hour period on July 14, 1975. Soil water samples were taken, as described previously, on July 17, 19, 23, and 30, 1975. On July 31, 1975, an additional pit was excavated near the Musselshell plot, where no water had been added, and soil samples for

Table 1 - Morphological characteristics of soils. Typical pedon of Cravel Gravelly Loam. Tentative Classification: Borollic Calciorthids, loamy-skeletal, carbonatic.

| | |
|---|---|
| A1 | 0-10 cm--Light brownish gray (10YR 6/2) gravelly loam, dark grayish brown (10YR 4/2) moist; weak fine granular structure; soft, very friable, slightly sticky, nonplastic; many fine roots throughout horizon; many fine irregular and tubular pores; calcium carbonate cutans on lower surfaces of fragments; 20 percent gravel; slightly effervescent; moderately alkaline pH 8.0; clear wavy boundary. (8-15 cm thick) |
| C1ca | 10-36 cm--Light gray (10YR 7/2) gravelly sandy loam; light brownish gray (10YR 6/2) moist; weak coarse subangular blocky structure; soft, very friable, nonsticky, nonplastic; common fine roots throughout horizon; common fine vesicular and tubular pores; calcium carbonate cutans on lower surfaces of fragments; 20 percent gravel; violently effervescent; moderately alkaline pH 8.2; clear wavy boundary. (25-35 cm thick) |
| C2ca | 36-71 cm--White (10YR 8/2) very gravelly sandy loam; light gray (10YR 7/2) moist; massive structure; soft, very friable, nonsticky, nonplastic, partially cemented with lime and silica; common fine roots throughout horizon; common fine interstitial pores; calcium carbonate cutans on sand and gravel; 50 percent gravel and 20 percent cobbles; violently effervescent; moderately alkaline pH 8.4; clear irregular boundary. |
| IICca | 71-152 cm--Light brownish gray (10YR 6/2) very gravelly loamy sand; brown (10YR 5/3) moist; single grain structure; loose, loose, nonsticky, nonplastic; many fine and medium interstitial pores; calcium carbonate cutans on lower surfaces of fragments; 50 percent gravel, 20 percent cobbles; slightly effervescent; moderately alkaline pH 8.4. |

Table 2 - Morphological characteristics of soils. Typical pedon of Musselshell Loam. Tentative Classification: Borollic Calciorthids, coarse-loamy, carbonatic.*

| | |
|---|---|
| A1 | 0-10 cm--Light brownish gray (10YR 6/2) light loam; dark grayish brown (10YR 4/2) moist; weak fine granular structure; slightly hard, very friable, slightly sticky, nonplastic; many fine roots throughout horizon; common irregular pores, few to common fine and medium tubular pores; calcium carbonate cutans on lower surfaces of fragments; 15 percent fine gravel; slightly effervescent; moderately alkaline pH 8.0; abrupt smooth boundary. (8-15 cm thick) |
| C1Ca | 10-20 cm--Light gray (10YR 7/3) loam; brown (10YR 5/3) moist; weak coarse subangular blocky structure; slightly hard; friable, slightly sticky, slightly plastic; common fine roots throughout horizon; common fine tubular pores; calcium carbonate cutans on lower surfaces of fragments; 15 percent fine gravel; strongly effervescent; moderately alkaline pH 8.0; clear smooth boundary. |
| C2ca | 20-56 cm--White (10YR 8/1) sandy loam; light gray (10YR 7/2) moist; very weak coarse subangular blocky structure; soft, very friable, nonsticky, nonplastic; common fine roots throughout horizon; common fine vesicular and tubular pores; calcium carbonate cutans on lower surfaces of fragments; 15 percent fine gravel; violently effervescent; moderately alkaline pH 8.0; clear wavy boundary. (36-51 cm thick) |
| C3ca | 56-81 cm--Light gray (10YR 7/2) very gravelly sandy loam; pale brown (10YR 6/3) moist; massive structure extremely hard, extremely firm, nonsticky, nonplastic, partially cemented with lime and silica; few fine roots matted around gravel; few fine interstitial pores; calcium carbonate cutans on sand and gravel; 50 percent gravel, 20 percent cobbles; violently effervescent; moderately alkaline pH 8.0; gradual wavy boundary. (25-30 cm thick) |

Table 2 - Continued

IICca 81-152 cm--Light brownish gray (10YR 6/2) very gravelly loamy sand; brown (10YR 5/3) moist; single grain structure; loose, loose, nonsticky, nonplastic; many fine and medium interstitial pores; calcium carbonate cutans on lower surfaces of fragments; 50 percent gravel, 20 percent cobbles; slightly effervescent; moderately alkaline pH 8.0.

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*This profile falls outside the range of the classification for Musselshell series by exceeding 35 percent rock fragments by volume in the 25 cm to 100 cm texture control section.

water determination were collected. In the semi-arid climate of the Madison Valley, all of the soil water available to native range has been depleted by the end of July in most years. Soil water samples collected at the end of July should be a good approximation of 15 bar water.

It was theorized the permeability of these two soils was limited by the rate of flow through the concentrated lime zone. An attempt was made to measure infiltration in this zone by excavating down to the concentrated lime zone and placing infiltration rings in it. The measured intake rates over a four hour period were in excess of those determined earlier on the research plots. These results were not considered conclusive as we were unable to use a buffer pond and the rings were nearly impossible to seal in the partially cemented gravelly Cca horizon. However, this horizon was more permeable than previously expected.

## Total Soil Water (Appendix 2)

Soils containing a large percentage of rock fragments commonly have a great variation in size and amount of fragments within short distances, both horizontally and vertically. Branson et al. (1965) described soils having

80 percent rock fragments greater than 2 millimeters in some areas and 10 percent in adjacent portions of the same profile. This variation is not uncommon in Madison County, Montana in soils formed from either transported or bedrock materials. Most of the water in a soil is held in the fine earth portion rather than by the fragments greater than 2 millimeters in diameter. Therefore, the water available to plants within any soil profile may vary widely just as the proportion of rock fragments do. Rock fragment content in the substratum of these two soils appears to be quite uniform. Four bulk samples of the substratum weighing 9 to 12 kilograms (20 to 28 pounds) each indicated 79, 80, 81, and 82 percent by weight rock fragments.

After 5 years of field soil survey in Madison County, Montana, I must agree with Reinhart (1961), "Measurement of soil moisture content in stony soils is at best a difficult job and accuracy obtained will of necessity be lower than for like determinations in stone-free soils". With soils in this study containing approximately 80 percent (by weight) rock fragments, excavation was determined to be the only possible way to collect soil water samples.

The percentage of water remaining in a soil 2 or 3 days after having been saturated and after free drainage has practically ceased is considered to be "field moisture capacity" (Glossary of Soil Science Terms 1975). Consequently, the first soil water sample was taken about 2.5 days (60 hours) after saturation. Small quantities of free water continued to drain for extended periods after saturation, so additional soil water samples were collected 5, 9, and 16 days after saturation. The available water capacities in a 152 centimeter depth were calculated to be 13.5 centimeters (5.3 inches) for the Cravel soil and 19.3 centimeters (7.6 inches) for the Musselshell soil (Appendix 1). This compares favorably with estimated available water capacities used by the Soil Conservation Service for these soils.

Although the surface was covered to prevent evapotranspiration, these very gravelly soils continued to lose significant amounts of gravitational water after the first sampling. The fourth sample of Cravel soil had only about 40 percent and the Musselshell soil about 60 percent of the soil water present in the first sample. Very little gravitational water may have been lost after the first sampling, however, if the plants were allowed to use the free water during this 16 day period.

The calcic horizons of these soils have as much as 80 percent calcium carbonate in the fine earth fraction. Some thin strata are lime cemented, but the cemented zone is not continuous. Layers of nearly clean gravel are separated by thin partially cemented zones in the underlying material. Gile (1961) states that carbonate accretions are often separated by soil matrix with little or no carbonates in the early stages of carbonate accumulation. Increasing accumulation leads to more continuous, more uniform distribution throughout the horizon. Not only do individual nodules grow and finally merge, they also form zones of restricted permeability, funneling the carbonate-saturated soil solution to previously non-cemented parts of the horizon. The development of cementation is shown by increasing hardness of the carbonate concentrations, by increase in bulk density, and by increased separation of primary mineral grains as carbonate crystals continue to grow (Brown 1956; Flach et al. 1969 and Gile et al. 1965 and 1966).

The Cravel and Musselshell soils have carbonatic mineralogy which is defined as "more than 40 percent by weight carbonates (expressed as $CaCO_3$) plus gypsum, and the carbonates are greater than 65 percent of the sum of carbonates and gypsum" (Soil Survey Staff 1975). Carbonatic mineralogy is determined on the fine earth portion (less than 2 millimeters) or the whole soil (less than 20 millimeters), whichever has a higher percentage of carbonates.

The soils studied in this research have greater than 40 percent $CaCO_3$ in the fine earth fraction as determined by a simple volume calcimeter. It is difficult to determine whether the less than 20 millimeter fraction would have an even higher percentage of carbonates. If the thick $CaCO_3$ coating on the larger fragments were physically removed in chips less than 20 millimeters in diameter, they too could be included. Many of the coatings on these rock fragments are nearly pure $CaCO_3$, so if included, they would most certainly influence the results. This is a question in the procedure for determining calcium carbonate equivalents for which I have been unable to find an answer. A well-defined standard procedure must be recognized to obtain precise measurements.

I question whether 40 percent $CaCO_3$ by itself has any real significance, unless it can be associated with the development of a petrocalcic horizon or at least an indicator of reduced permeability or reduced root penetration.

After working with highly calcareous soils in Madison County, Montana and discussing the significance of the level of $CaCO_3$ in soils with the Soil Staff of the Soil Conservation Service in Montana, I must agree with Anter et al. (1973) that once $CaCO_3$ comprises 10 to 15 percent of the soil component it controls the soil's biological and chemical characteristics. Further increases in $CaCO_3$ content above 10 to 15 percent have little effect on plant growth.

These soils could be approaching the early stages of the development of a petrocalcic horizon. Several stages in the build up of carbonate horizons are recognized (Gile et al. 1966 and Birkeland 1974). In gravelly sediments, the morphogenetic sequence of carbonate accumulation is: I. Carbonate forms thin discontinuous pebble coatings on the undersides of coarse fragments. Carbonates probably accumulate on the undersides of coarse fragments first because downward moving water tends to collect there. II. Carbonate continuously coats pebbles and fills some interstices between pebbles. III. Carbonate continuously coats skeletal grains and plugs interstices to cement the soil. IV. Carbonate forms a laminar horizon on top of an indurated petrocalcic horizon. Very gravelly soils have less total pore space than non-gravelly soils, consequently petrocalcic horizons form much more rapidly in very gravelly soils. The two soils studied in this research are in stage II or III of the morphogenetic sequence of carbonate accumulation.

The formation of calcic and petrocalcic horizons in arid and semi-arid soils is generally attributed to soil-forming processes. The role that the physics of soil water movement plays in the accumulation of carbonates in these layered soils has been largely overlooked. Downward movement of soil water is restricted when fine textured soils are underlain by sand and gravel layers. Water penetrates the fine textured soil uniformly both laterally and vertically until the wetting front reaches the gravel. It will not enter the coarse layers until sufficient water accumulates to nearly saturate the fine textured soil. It will then leak through at some localized point and move rapidly downward, leaving the surrounding gravel dry, while the finer textured soil immediately above remains nearly saturated (Miller 1969). This phenomenon is well demonstrated in these Cravel and Musselshell soils by the soil water data (Appendix 2). The loamy upper part of these profiles had 2 to 3 times the expected soil water for these types of materials. A high proportion of the total soil water remained above the contact of the loamy soil and the underlying material throughout the study period.

The linear relationship of total water intake with time (Appendix 1d and 1i) is not typical of most soils. This unusual condition can be attributed to the accumulation of water at the interface of the loamy soil and the underlying very gravelly soil.

In layered soils of semi-arid regions like the Madison Valley, precipitation is often insufficient to enter sand and gravel underlying a finer textured soil. Calcium carbonate, silica, and other salts are deposited at or near the top of the gravel layers as water is removed by evapotranspiration. Carbonates continue to accumulate with time until the voids become plugged and water percolation through the zone is greatly restricted. Regardless of the actual process involved in calcic horizon formation, the importance of water movement and its impedence is evident.

# CONCLUSIONS

1. The results conclusively demonstrate these Cravel and Musselshell soils have moderate permeability. Saturated hydraulic conductivities were 2.5 to 3.5 centimeters per hour (1.0 to 1.4 inches per hour) near the middle of the moderate permeability range of 1.5 to 5.0 centimeters per hour (0.6 to 2.0 inches per hour).

2. The maximum available water capacity for this Cravel soil is 13.5 centimeters (5.3 inches) and for this Musselshell soil is 19.3 centimeters (7.6 inches) in a 152 centimeter (60 inch) depth. Any additional water readily drains away.

3. The standard definition for "field moisture capacity" does not apply to these Cravel and Musselshell soils. The accumulation of water at the interface of the loamy soil and the underlying very gravelly soil restricts normal gravitational water drainage.

4. A well-defined standard procedure for determining calcium carbonate equivalents is needed.

# RECOMMENDATIONS

These soils are not suited to flood irrigation. Their limited available water capacities require frequent, light irrigations. General recommendations for sprinkler irrigation on this Cravel soil are to replace 5.0 to 6.0 centimeters (2.0 to 2.5 inches) soil water every 8 to 10 days during the period of peak crop use. General recommendations for sprinkler irrigation on this Musselshell soil are to replace 7.5 centimeters (3 inches) of soil water every 12 days during the period of peak crop use. Where these soils occur in complex, as they do in the study area, irrigation management should be based on the Cravel soil.

# APPENDICES

# APPENDIX 1

## Field Saturated Hydraulic Conductivity Data

The data are arranged by soil series name. Pond refers to the large 3.0 meter (10 foot) square buffer ponds. Ring refers to the infiltration ring placed inside the pond. Time of reading is recorded in military time. The term "Fill" refers to placement of water in the pond. Hook gage reading and water intake are recorded in inches. Infiltration curves and total water intake curves are included to better interpret the data.

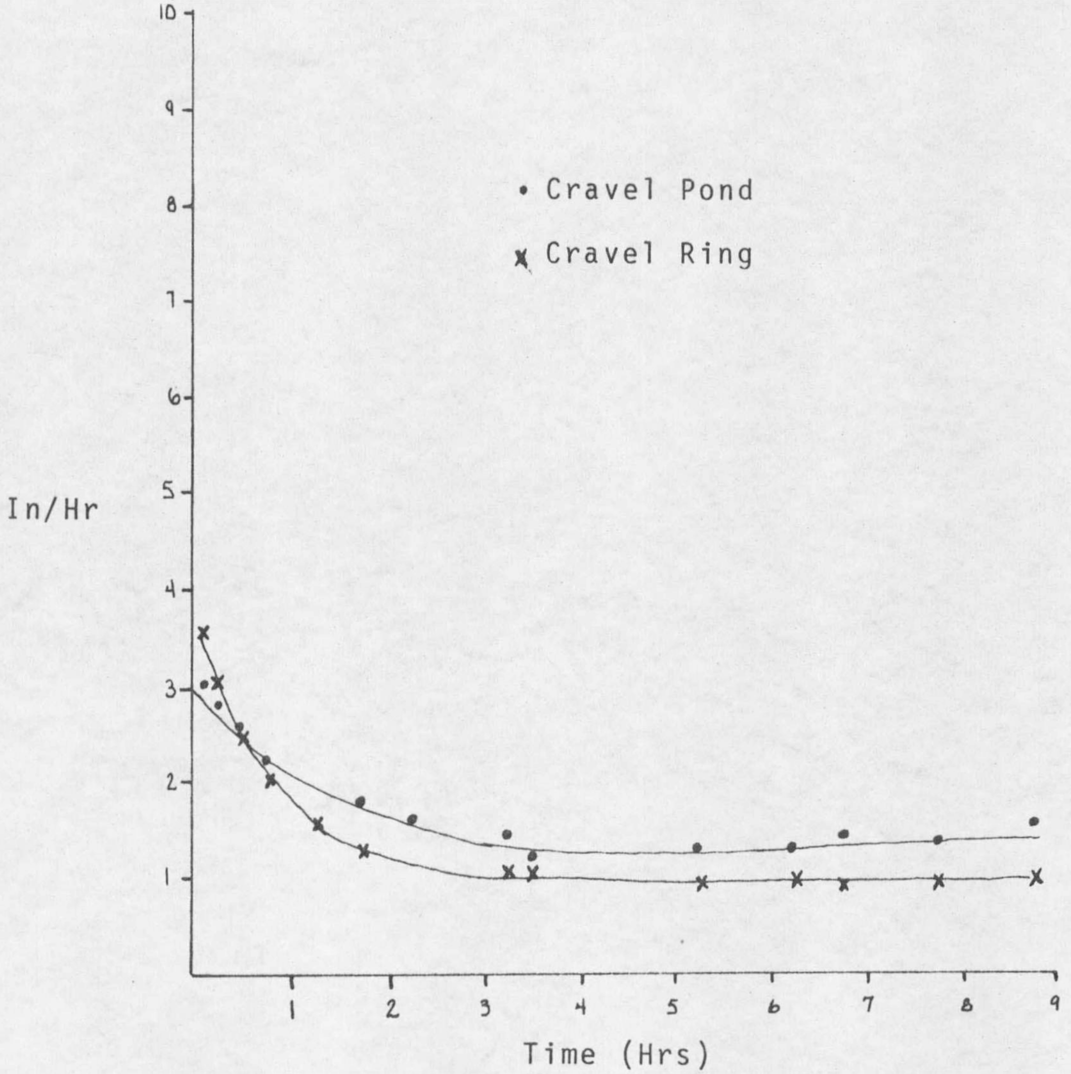
Appendix 1a-Continued

| Cravel Pond | Time of Reading | Hook Gage Reading | Water Intake |
|---|---|---|---|
| | | in | |
| 7-14-75 | 10:50 | 8.15 | |
| | 10:55 | 7.90 | .25 |
| | 11:00 | 7.65 | .25 |
| | 11:05 | 7.45 | .20 |
| | 11:10 | 7.20 | .25 |
| | Fill | 8.50 | |
| | 11:15 | 8.35 | .15 |
| | 11:20 | 8.15 | .20 |
| | 11:25 | 7.95 | .20 |
| | 11:30 | 7.80 | .15 |
| | 11:40 | 7.35 | .45 |
| | Fill | 9.10 | |
| | 11:50 | 8.80 | .30 |
| | 12:00 | 8.45 | .35 |
| | 12:30 | 7.60 | .85 |
| | Fill | 8.60 | |
| | 13:05 | 7.75 | .85 |
| | 14:02 | 6.40 | 1.35 |
| | 14:17 | 6.10 | .30 |
| | Fill | 9.05 | |
| | 15:00 | 7.75 | 1.30 |
| | 16:00 | 6.50 | 1.25 |
| | Fill | 9.25 | |
| | 17:00 | 7.90 | 1.30 |
| | 17:30 | 7.20 | .70 |
| | Fill | 9.45 | |
| | 18:30 | 8.10 | 1.35 |
| | 19:30 | 6.55 | 1.55 |
| | Fill | 9.00 | |

Appendix 1b- Continued

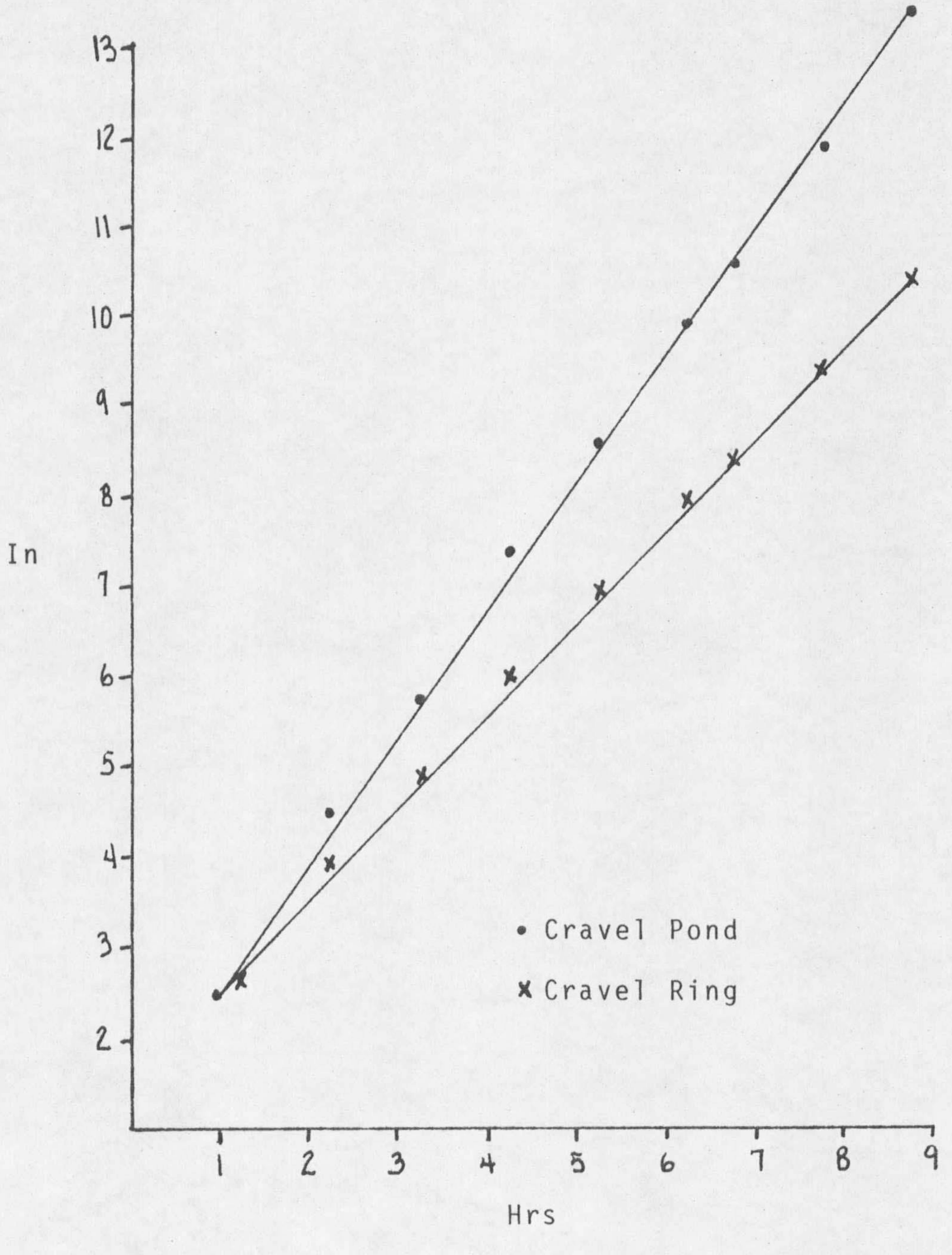
| Cravel Ring | Time of Reading | Hook Gage Reading | Water Intake |
|---|---|---|---|
| | | -------------in | ---------- |
| 7-14-75 | 10:45 | 6.95 | |
| | 10:50 | 6.65 | .30 |
| | Fill | 7.70 | |
| | 10:55 | 7.45 | .25 |
| | 11:00 | 7.25 | .20 |
| | 11:05 | 7.00 | .25 |
| | 11:10 | 6.80 | .20 |
| | Fill | 8.20 | |
| | 11:15 | 8.05 | .15 |
| | 11:20 | 7.85 | .20 |
| | 11:25 | 7.65 | .20 |
| | 11:30 | 7.55 | .10 |
| | 11:40 | 7.20 | .35 |
| | Fill | 9.10 | |
| | 11:50 | 8.90 | .20 |
| | 12:00 | 8.65 | .25 |
| | 12:30 | 8.00 | .65 |
| | 13:05 | 7.40 | .60 |
| | 14:00 | 6.40 | 1.00 |
| | 14:15 | 6.15 | .25 |
| | Fill | 8.00 | |
| | 15:00 | 7.10 | .90 |
| | 16:00 | 6.20 | .90 |
| | Fill | 8.15 | |
| | 17:00 | 7.10 | 1.05 |
| | 17:30 | 6.65 | .45 |
| | Fill | 8.50 | |
| | 18:30 | 7.50 | 1.00 |
| | 19:30 | 6.40 | 1.10 |
| | Fill | 8.85 | |

Appendix 1c- Continued



Cravel Infiltration Curves

Appendix 1d- Continued



Total water intake of Cravel soil.

Appendix 1e- Continued

| Musselshell Pond | Time of Reading | Hook Gage Reading | Water Intake |
|---|---|---|---|
| | | ------------in | ---------- |
| 7-14-75 | 13:30 | 6.80 | |
| | 13:35 | 6.15 | .65 |
| | 13:40 | 5.80 | .35 |
| | Fill | 7.40 | |
| | 13:45 | 7.20 | .20 |
| | 13:50 | 6.85 | .35 |
| | 13:55 | 6.45 | .40 |
| | Fill | 7.40 | |
| | 14:00 | 7.20 | .20 |
| | 14:05 | 7.05 | .15 |
| | 14:15 | 6.60 | .45 |
| | 14:25 | 6.25 | .35 |
| | 14:35 | 5.85 | .40 |
| | Fill | 7.45 | |
| | 14:45 | 7.15 | .30 |
| | 15:15 | 6.25 | .90 |
| | 15:45 | 5.35 | .90 |
| | Fill | 7.50 | |
| | 16:45 | 5.95 | 1.55 |
| | 17:15 | 5.50 | .45 |
| | Fill | 8.25 | |
| | 18:15 | 6.70 | 1.55 |
| | 19:15 | 5.40 | 1.30 |
| | Fill | 8.25 | |

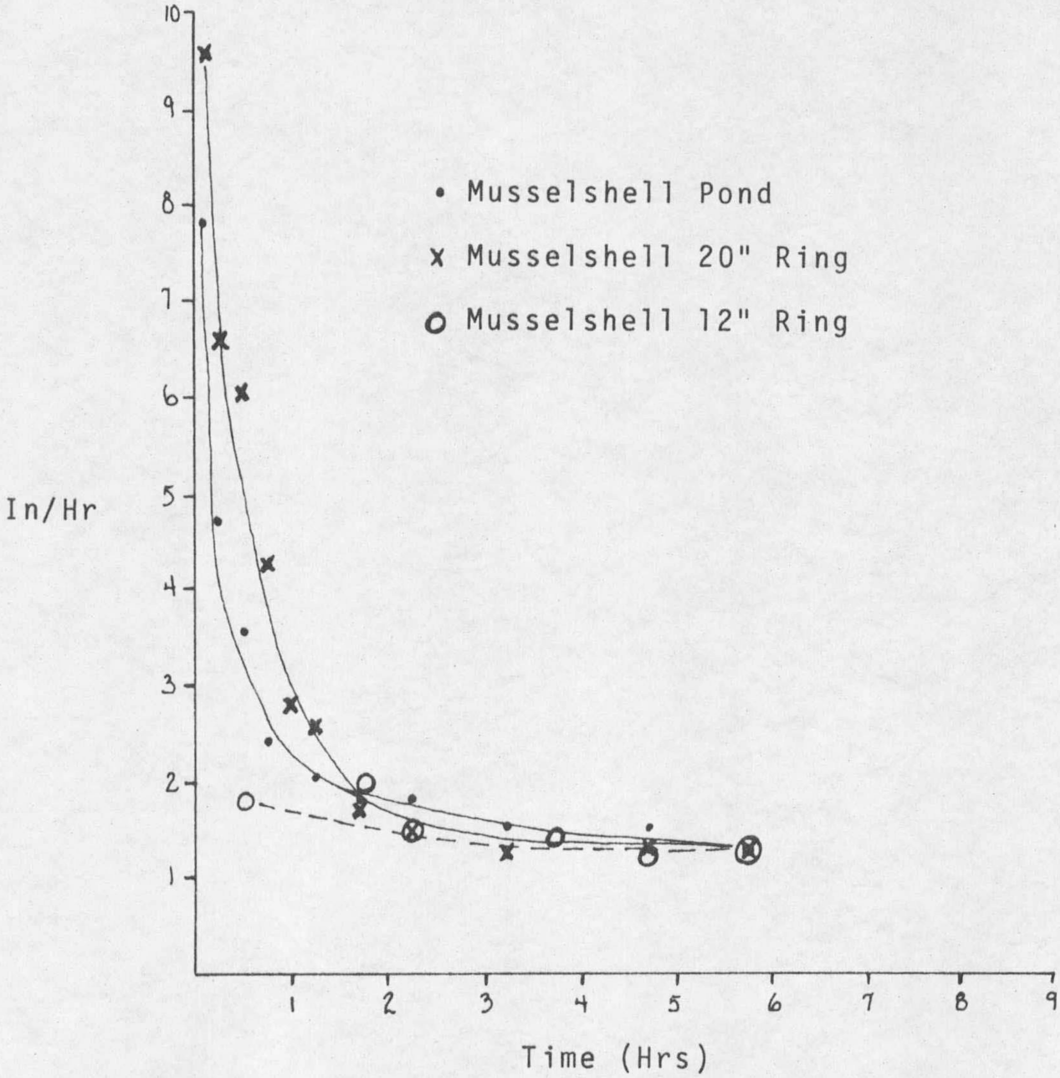
Appendix 1f- Continued

| Musselshell 20" Ring | Time of Reading | Hook Gage Reading | Water Intake |
|---|---|---|---|
| | | in | |
| 7-14-75 | 13:30 | 6.90 | |
| | 13:35 | 6.10 | .80 |
| | Fill | 5.90 | |
| | 13:40 | 5.60 | .30 |
| | Fill | 8.25 | |
| | 13:45 | 7.70 | .55 |
| | 13:50 | 7.00 | .70 |
| | 13:55 | 6.45 | .55 |
| | Fill | 8.10 | |
| | 14:00 | 7.60 | .50 |
| | 14:05 | 7.20 | .40 |
| | 14:15 | 6.55 | .65 |
| | 14:25 | 6.05 | .50 |
| | 14:35 | 5.60 | .45 |
| | Fill | 7.95 | |
| | 14:45 | 7.60 | .35 |
| | 15:15 | 6.75 | .85 |
| | 15:45 | 6.00 | .75 |
| | Fill | 7.60 | |
| | 16:45 | 6.35 | 1.25 |
| | 17:15 | 5.95 | .40 |
| | Fill | 8.35 | |
| | 18:15 | 7.00 | 1.35 |
| | 19:15 | 5.70 | 1.30 |
| | Fill | 8.50 | |

Appendix 1g- Continued

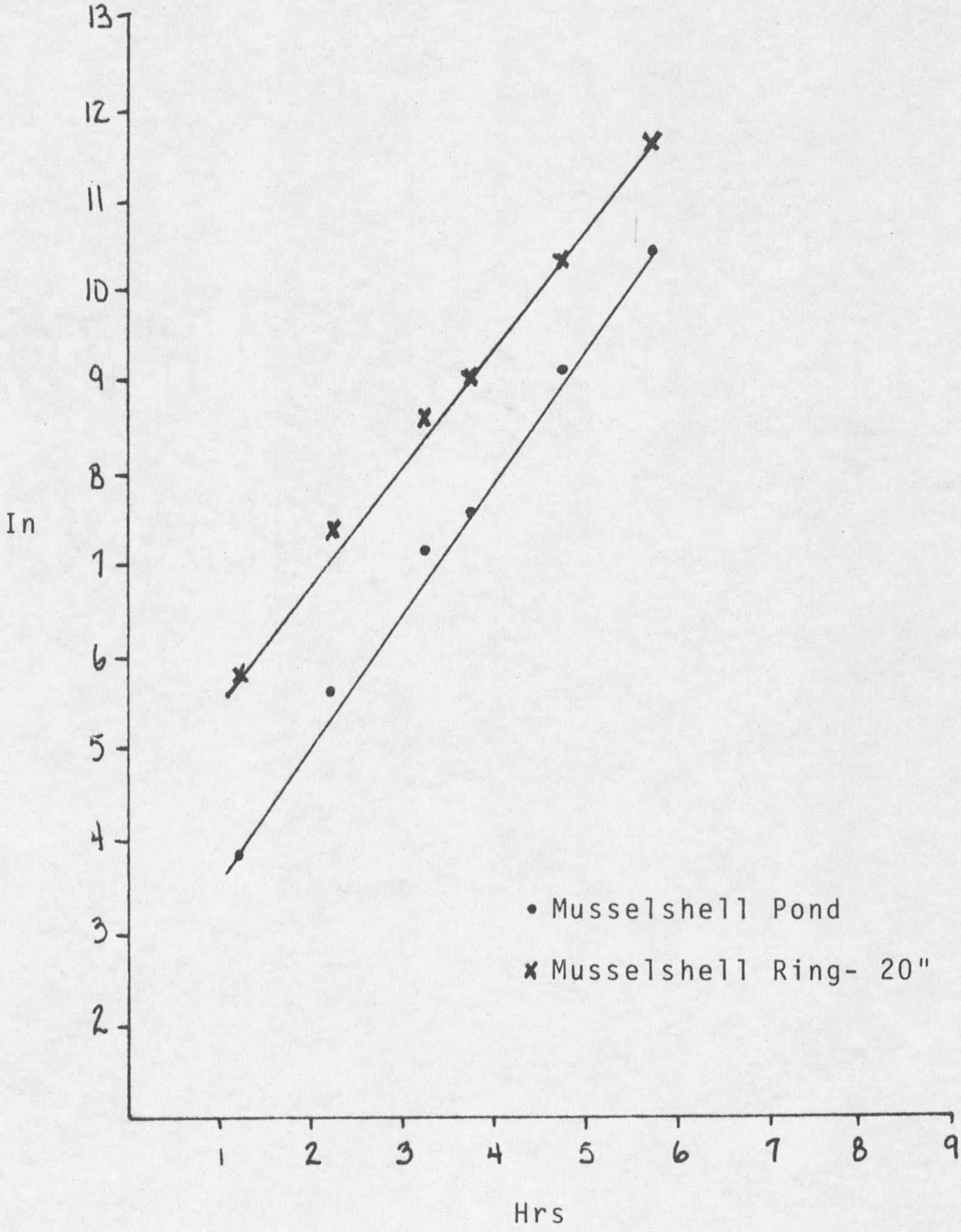
| Musselshell 12" Ring | Time of Reading | Hook Gage Reading | Water Intake |
|---|---|---|---|
| | | ------------in | ---------- |
| 7-14-75 | 13:58 | 1.50 | |
| | 14:03 | 1.35 | .15 |
| | 14:08 | 1.20 | .15 |
| | 14:18 | .90 | .30 |
| | 14:28 | .70 | .20 |
| | Fill | 3.20 | |
| | 14:46 | 2.85 | .35 |
| | 15:15 | 1.85 | 1.00 |
| | 15:45 | 1.10 | .75 |
| | Fill | 3.75 | |
| | 16:50 | 2.30 | 1.45 |
| | 17:15 | 1.65 | .65 |
| | Fill | 3.90 | |
| | 18:15 | 2.60 | 1.30 |
| | 19:15 | 1.30 | 1.30 |
| | Fill | 4.65 | |

Appendix 1h- Continued



Musselshell Infiltration Curves

Appendix li- Continued



Total water intake of Musselshell soil.

# APPENDIX 2

## Basic Soil-Water Data

The data are arranged by soil series name and sample date. The dry weight of soil sample, water loss, and the amount of material greater than 2 millimeters in diameter were determined in grams. The percent water on the basis of the dry weight of fine earth was calculated as follows:

$$\text{Wt. \% } H_2O\text{, fines} = \frac{\text{Wt. of } H_2O}{\text{Sample dry Wt.-Wt. of 2 mm-material}} \times 100$$

Calculations for the following data are (See column headings): (B)X(C) = D, (D)X(E) = F, and (A)X(F) = G. Available water capacity can be determined for each sampling date by subtracting the total of column (G) for the Musselshell dry soil, sampled 7-31, from the total of column (G) for each sampling date.

Appendix 2 - Continued

Gravel

| Date | (A) | (B) | (C) | (D) | (E) | (F) | (G) |
|---|---|---|---|---|---|---|---|
| | Depth | Wt. of $H_2O$ Fine Earth | Bulk Density Fine Earth | Vol. of $H_2O$ Fine Earth | Vol. of Fine Earth | Vol. of $H_2O$ Whole Soil | |
| | cm | % | $g/cm^3$ | % | % | % | cm |
| 7-17 | 0-10 | 25.0 | 1.1 | 27.5 | 80 | 22.0 | 2.2 |
| | 10-20 | 35.6 | 1.3 | 46.3 | 80 | 37.0 | 3.7 |
| | 20-35 | 46.1 | 1.43 | 65.9 | 80 | 52.7 | 7.9 |
| | 35-55 | 35.3 | 1.43 | 50.5 | 30 | 15.1 | 3.0 |
| | 55-80 | 27.6 | 1.3 | 35.9 | 30 | 10.8 | 2.7 |
| | 80-110 | 21.4 | 1.3 | 27.8 | 30 | 8.3 | 2.5 |
| | 110-141 | 19.3 | 1.3 | 25.1 | 30 | 7.5 | 2.3 |
| | 141-152 | 15.2 | 1.3 | 19.8 | 30 | 5.9 | 0.6 |
| 7-19 | 0-10 | 27.6 | 1.1 | 30.4 | 80 | 24.3 | 2.4 |
| | 10-20 | 31.4 | 1.3 | 40.8 | 80 | 32.7 | 3.3 |
| | 20-35 | 30.6 | 1.43 | 43.8 | 80 | 35.0 | 5.2 |
| | 35-55 | 25.3 | 1.43 | 36.2 | 30 | 10.8 | 2.2 |
| | 55-80 | 22.1 | 1.3 | 28.7 | 30 | 8.6 | 2.2 |
| | 80-110 | 20.8 | 1.3 | 27.0 | 30 | 8.1 | 2.5 |
| | 110-141 | 13.5 | 1.3 | 17.6 | 30 | 5.3 | 1.6 |
| | 141-152 | 15.0 | 1.3 | 19.5 | 30 | 5.8 | 0.6 |
| 7-23 | 0-10 | 24.1 | 1.1 | 26.5 | 80 | 21.2 | 2.1 |
| | 10-20 | 32.5 | 1.3 | 42.2 | 80 | 33.8 | 3.4 |
| | 20-35 | 40.5 | 1.43 | 57.9 | 80 | 46.3 | 6.9 |
| | 35-55 | 32.1 | 1.43 | 45.9 | 30 | 13.8 | 2.8 |
| | 55-80 | 24.1 | 1.3 | 31.3 | 30 | 9.4 | 2.4 |
| | 80-110 | 15.0 | 1.3 | 19.5 | 30 | 5.8 | 1.8 |
| | 110-141 | 14.2 | 1.3 | 18.5 | 30 | 5.5 | 1.7 |
| | 141-152 | 12.6 | 1.3 | 16.4 | 30 | 4.9 | 0.5 |

Appendix 2 - Continued

Gravel--Continued

| Date | (A) Depth cm | (B) Wt. of $H_2O$ Fine Earth % | (C) Bulk Density Fine Earth g/cm$^3$ | (D) Vol. of $H_2O$ Fine Earth % | (E) Vol. of Fine Earth % | (F) Vol. of $H_2O$ Whole Soil % | (G) cm |
|---|---|---|---|---|---|---|---|
| 7-30 | 0-10 | 28.1 | 1.1 | 30.9 | 80 | 24.7 | 2.5 |
| | 10-20 | 31.1 | 1.3 | 40.4 | 80 | 32.3 | 3.2 |
| | 20-35 | 21.4 | 1.43 | 30.6 | 80 | 24.5 | 3.7 |
| | 35-55 | 21.1 | 1.43 | 30.2 | 30 | 9.1 | 1.8 |
| | 55-80 | 20.1 | 1.3 | 26.1 | 30 | 7.8 | 2.0 |
| | 80-110 | 14.2 | 1.3 | 18.5 | 30 | 5.5 | 1.7 |
| | 110-141 | 10.0 | 1.3 | 13.0 | 30 | 3.9 | 1.2 |
| | 141-152 | 16.2 | 1.3 | 21.1 | 30 | 6.3 | 0.6 |

Appendix 2 - Continued

Musselshell

| Date | (A) Depth cm | (B) Wt. of $H_2O$ Fine Earth % | (C) Bulk Density Fine Earth $g/cm^3$ | (D) Vol. of $H_2O$ Fine Earth % | (E) Vol. of Fine Earth % | (F) Vol. of $H_2O$ Whole Soil % | (G) cm |
|---|---|---|---|---|---|---|---|
| 7-17 | 0-10 | 26.5 | 1.1 | 29.2 | 85 | 24.8 | 2.5 |
| | 10-20 | 38.5 | 1.3 | 50.0 | 85 | 42.5 | 4.2 |
| | 20-35 | 36.5 | 1.3 | 47.4 | 80 | 38.0 | 5.7 |
| | 35-55 | 34.9 | 1.43 | 49.9 | 80 | 39.9 | 8.0 |
| | 55-80 | 42.5 | 1.43 | 60.8 | 30 | 18.2 | 4.6 |
| | 80-110 | 25.4 | 1.3 | 33.0 | 30 | 9.9 | 3.0 |
| | 110-141 | 16.9 | 1.3 | 22.0 | 30 | 6.6 | 2.0 |
| | 141-152 | 18.5 | 1.3 | 24.0 | 30 | 7.2 | 0.7 |
| 7-19 | 0-10 | 30.7 | 1.1 | 33.7 | 85 | 28.7 | 2.9 |
| | 10-20 | 37.2 | 1.3 | 48.4 | 85 | 41.1 | 4.1 |
| | 20-35 | 27.6 | 1.3 | 35.9 | 80 | 28.7 | 4.3 |
| | 35-55 | 30.9 | 1.43 | 44.2 | 80 | 35.4 | 7.1 |
| | 55-80 | 19.4 | 1.43 | 27.7 | 30 | 8.3 | 2.1 |
| | 80-110 | 17.8 | 1.3 | 23.1 | 30 | 6.9 | 2.1 |
| | 110-141 | 14.1 | 1.3 | 18.3 | 30 | 5.5 | 1.7 |
| | 141-152 | 13.2 | 1.3 | 17.2 | 30 | 5.2 | 0.5 |
| 7-23 | 0-10 | 24.9 | 1.1 | 27.4 | 85 | 23.3 | 2.3 |
| | 10-20 | 31.0 | 1.3 | 40.3 | 85 | 34.3 | 3.4 |
| | 20-35 | 30.1 | 1.3 | 39.1 | 80 | 31.3 | 4.7 |
| | 35-55 | 33.0 | 1.43 | 47.2 | 80 | 37.8 | 7.6 |
| | 55-80 | 23.6 | 1.43 | 33.7 | 30 | 10.1 | 2.5 |
| | 80-110 | 15.4 | 1.3 | 20.0 | 30 | 6.0 | 1.8 |
| | 110-141 | 13.1 | 1.3 | 17.0 | 30 | 5.1 | 1.6 |
| | 141-152 | 14.8 | 1.3 | 19.2 | 30 | 5.8 | 0.6 |

Appendix 2 - Continued

Musselshell--Continued

| Date | (A)<br>Depth | (B)<br>Wt. of $H_2O$ Fine Earth | (C)<br>Bulk Density Fine Earth | (D)<br>Vol. of $H_2O$ Fine Earth | (E)<br>Vol. of Fine Earth | (F)<br>Vol. of $H_2O$ Whole Soil | (G) |
|---|---|---|---|---|---|---|---|
| | cm | % | g/cm$^3$ | % | % | % | cm |
| 7-30 | 0-10 | 24.3 | 1.1 | 26.7 | 85 | 22.7 | 2.3 |
| | 10-20 | 31.2 | 1.3 | 40.6 | 85 | 34.5 | 3.4 |
| | 20-35 | 27.6 | 1.3 | 35.9 | 80 | 28.7 | 4.3 |
| | 35-55 | 30.4 | 1.43 | 43.5 | 80 | 34.8 | 7.0 |
| | 55-80 | 15.7 | 1.43 | 22.5 | 30 | 6.7 | 1.7 |
| | 80-110 | 14.7 | 1.3 | 19.1 | 30 | 5.7 | 1.8 |
| | 110-141 | 12.9 | 1.3 | 16.8 | 30 | 5.0 | 1.5 |
| | 141-152 | 15.6 | 1.3 | 20.3 | 30 | 6.1 | 0.6 |

Appendix 2 - Continued

Musselshell Dry Soil

| Date | (A) Depth cm | (B) Wt. of $H_2O$ Fine Earth % | (C) Bulk Density Fine Earth g/cm$^3$ | (D) Vol. of $H_2O$ Fine Earth % | (E) Vol. of Fine Earth % | (F) Vol. of $H_2O$ Whole soil % | (G) cm |
|---|---|---|---|---|---|---|---|
| 7-31 | 0-10 | 12.1 | 1.1 | 13.3 | 85 | 11.3 | 1.1 |
| | 10-20 | 12.0 | 1.3 | 15.6 | 85 | 13.3 | 1.3 |
| | 20-35 | 12.3 | 1.3 | 16.0 | 80 | 12.8 | 1.9 |
| | 35-55 | 12.2 | 1.43 | 17.4 | 80 | 14.0 | 2.8 |
| | 55-80 | 13.1 | 1.43 | 18.7 | 30 | 5.6 | 1.4 |
| | 80-110 | 9.4 | 1.3 | 12.2 | 30 | 3.7 | 1.1 |
| | 110-141 | 12.1 | 1.3 | 15.7 | 30 | 4.7 | 1.4 |
| | 141-152 | 11.5 | 1.3 | 15.0 | 30 | 4.5 | 0.5 |

# APPENDIX 3

## LABORATORY SATURATED HYDRAULIC CONDUCTIVITY

| | I | | II | | III | |
|---|---|---|---|---|---|---|
| hr | ml | ml/hr | ml | ml/hr | ml | ml/hr |
| 12 | 802 | 67 | 882 | 68.5 | 695 | 58 |
| 12 | 702 | 58.5 | 672 | 56 | 610 | 51 |
| 24.5 | 1296 | 53 | 1235 | 50.4 | 1120 | 46 |
| 24 | 1104 | 46 | 1073 | 44.7 | 981 | 41 |
| 32 | 1359 | 42.5 | 1332 | 41.6 | 1214 | 38 |
| 17 | 690 | 40.6 | 673 | 39.6 | 600 | 35 |
| 22 | 904 | 41 | 906 | 41.2 | 774 | 35 |
| 23.5 | 994 | 42.3 | 996 | 42.4 | 838 | 35.7 |

## HYDRAULIC CONDUCTIVITY CALCULATIONS

$$\frac{Q}{A\ t} = K\ \frac{h}{L} \qquad K = \frac{Q\ L}{t\ A\ h} = \frac{Q\ (7\ \text{cm})}{t\ (50.24\ \text{cm}^2)\ \text{X}\ 10\ \text{cm}}$$

Q is the volume of water passing through the material in time (t); A is the area of the soil column and K is the average hydraulic conductivity in the soil interval (L) over which there is a hydraulic-head difference (h). (h) in replication III was 9.5 centimeters.

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