Irrigation-related sediment deposition and suspended sediment effects on saturated hydraulic conductivity

by Noorjahan Parwana

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Soils
Montana State University

Abstract:
The Powder River serves as an important irrigation water source to local ranchers and farmers despite high concentrations of suspended sediment in the water.

Deposition of sediments from flood irrigation with sediment-laden water has been shown to dramatically alter the textural class of soils (U.S.D.A., 1950) and decrease irrigation efficiency (WeStcot and Ayers, 1984).

Two laboratory studies were conducted investigating sediment impacts on soil properties. In Study I, soil columns were leached with solutions containing various combinations of suspended sediment, salinity, and sodicity levels. The purpose of the study was to determine the effect of suspended sediment concentration in irrigation water on saturated hydraulic conductivity (Ksat).

In the second study, paired comparisons were made of particle size distribution between surficial soil samples collected from adjacent irrigated and non-irrigated sites. The purpose of Study II was to determine if irrigation with sediment-laden irrigation water alters surface soil textural class.

Suspended sediment shows no effect on Ksat. Impacts on Ksat were achieved as a result of salinity and sodicity. Significant reduction in Ksat was achieved in soil columns leached with solutions containing a combination of low salinity and high sodicity levels, a combination unlikely to occur in Powder River waters. Data provide evidence that deposition of suspended sediment from Powder River irrigation water results in a finer soil textural class on irrigated soils, compared to similar non-irrigated soils.

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Noorjahan Parwana

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Noorjahan Parwana

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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Noorjahan Parwana

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ABSTRACT

The Powder River serves as an important irrigation water source to local ranchers and farmers despite high concentrations of suspended sediment in the water. Deposition of sediments from flood irrigation with sediment-laden water has been shown to dramatically alter the textural class of soils (U.S.D.A., 1950) and decrease irrigation efficiency (Westcot and Ayers, 1984).

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CHAPTER 1

INTRODUCTION

Expansion of irrigated acreage is impacting water quality and availability on many rivers throughout the arid west. Water quality issues are magnified on the Powder River, in southeastern Montana, which has been described as "Too thick to drink and too thin to plow." The priority water right ("first in time, first in right") further complicates matters since irrigation by one farmer can completely deplete water availability to the downstream irrigator. Often, even when adequate amounts of water are available for all interested parties, the quality of that water is marginal with respect to salinity, sodium hazard, and suspended sediment load. The Powder River Development Council (P.R.D.C.) and the Montana Department of Natural Resources and Conservation (D.N.R.C.) are concerned that oil exploration, oil well development, and a proposed reservoir on Clear Creek in Wyoming could further elevate salinity and sodicity levels of Powder River water.

Several investigators have analyzed water-quality trends in the Powder River basin with inconsistent results. The DNRC (Gallagher, 1986), Wells and Shertz (1983), and

Gallagher (1986) predict an increase in total dissolved solids (TDS) while others (Smith and Alexander, 1985; Carey, 1989) find no such trends. Differences in these predictions may be due to differences in methods of analysis and differences in the time frame during which data were collected. Trend-analyses on sodium adsorption ratio (SAR) predict significant annual increases (Gallagher, 1986 and Carey, 1989).

Data from the U.S.G.S. gauging station at Locate, MT corresponding to 1975-1984 revealed that average annual electrical conductivity (EC) was 1.9 deciSiemens per meter (dSm^{-1}) and SAR was 4.8 (Gallagher, 1986). EC increased 70% (from 1.65 to 1.84 dSm^{-1}) and SAR increased 76% (from 2.9 to 4.7) when data from 1954-1957 was compared to data for 1975-1984 (Gallagher, 1986).

The Powder River is noteworthy with respect to the amount of sediment transported by the river, however, no increasing trend is predicted for suspended sediment (Smith and Alexander, 1985). Scour effect, which causes an increase in suspended sediment in the upper reach of a river and deposition in the lower reaches, is an important feature of the Powder River. The U.S.G.S. (1986) calculated an average of 4.7 million tons of suspended sediment are transported past Arvada, Wyoming each year, and 2.7 million tons are carried past Locate, Montana, about 150 miles north of Arvada (Figure 1). Thus 2.10 million tons of sediment

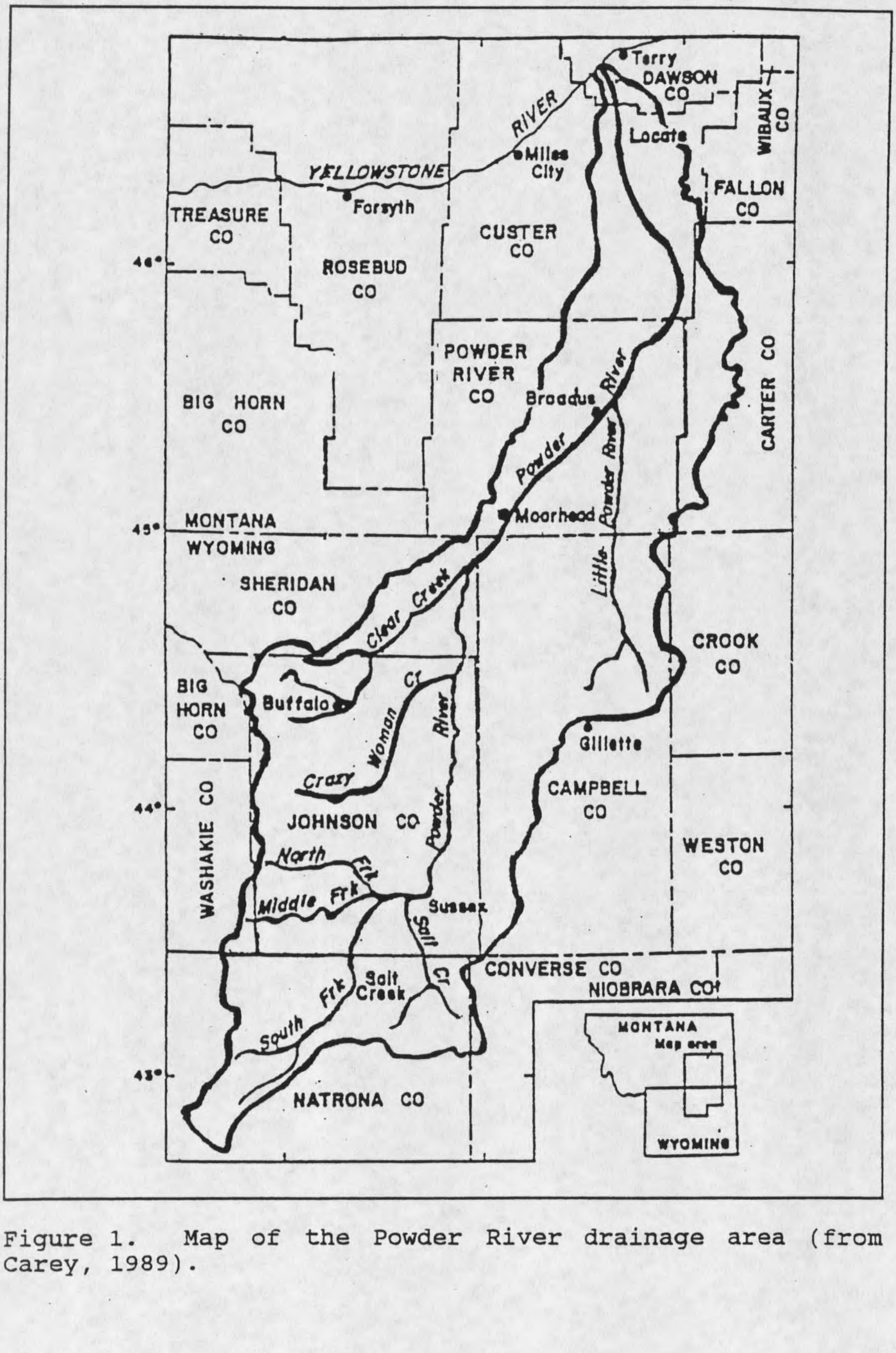

Figure 1. Map of the Powder River drainage area (from Carey, 1989).

per year are deposited in the reach of the Powder River between Arvada and Locate. Silt and clay account for ~89% of the suspended sediment in the entire basin (U.S.G.S., 1986). Eighty samples collected at Locate contained an average of 60% clay, 26% silt, and 14% sand. Sediment concentrations greater than 20,000 mg L^{-1} are not uncommon in the Powder River.

Deposition of sediments from flood irrigation with sediment-laden water has been shown to dramatically change the textural class of soils (U.S.D.A., 1950). Subsequently, irrigation efficiency may be reduced with decreased soil uniformity (Ayers and Westcot, 1976) due to increased variability in soil permeability and water-holding capacity. Other farm-related costs due to sediment in irrigation water are increased pumping costs, accelerated deterioration of irrigation equipment, added time and expense of removing sediment deposits from canals, increased potential for transport and accumulation of toxins or pollutants, and reduced yields due to the inability of seedlings to emerge through surface seals (Brown et al., 1974; James and King, 1984; Magleby et al., 1989). Surface seals created during sediment deposition, overland flow during irrigation, and raindrop impact have been shown to reduce infiltration by fifty percent (Segeren and Trout, 1989; Eisenhauer, 1983).

Despite marginal quality of irrigation water, the Powder River is an important resource for irrigation of cultivated crops in southeast Montana. Ninety-two percent of the water used is for irrigation (U.S.G.S., 1986). A recent survey of irrigators on the Powder River in Montana (Bauder, 1990, personal communication) estimated 16,000 acres are flood irrigated in Prairie, Custer, and Powder River counties. The three most urgent problems associated with irrigation cited by the irrigators were: i) deteriorating water quality, ii) decreasing water supply, and iii) increasing cost of pumping.

Irrigators utilizing Powder River water in parts of Custer and Prairie Counties visually assess sediment load of the irrigation water to decide whether or not to irrigate (Scott Foulger, 1990, Powder River irrigator, personal communication). Irrigators claim that irrigation time is reduced when river water carries a high sediment load. This time savings is equated with more efficient irrigation.

The relationship between irrigation water salinity, SAR, and soil physical properties is well established. The same is not true with respect to sediment deposition on irrigated land. Most studies on the relationship between irrigation and sediment have focused on sediment loss from the field rather than the impact of sediment transported onto the field. This thesis presents the results of an investigation to determine if irrigation with sediment-rich Powder River water, has any quantifiable effects on the surface texture or on movement of water through the soil.

Objectives

Salinity and Na concentrations of the Powder River are important variables with respect to management of Powder River soils and water. Consequently, several studies have been undertaken to project future trends in the quality of the Powder River. Despite the fact that the Powder River carries relatively high concentrations of suspended sediment, and that current irrigation management decisions are being made based on sediment load of the irrigation water, no investigations have been made of the impact of sediment deposition on the soils or soil physical properties along the Powder River. The objectives of this study were: i) to determine if sediment in various water-quality regimes, with respect to EC and SAR, affects the hydraulic conductivity (K) of a representative Powder River irrigated soil; and ii) to determine if irrigation with Powder River water has altered the surface soil textural class of an irrigated soil compared to the same soil under non-irrigated conditions.

CHAPTER 2

LITERATURE REVIEW

Sediment

Many irrigators in the intermountain region of the U.S. are faced with problems stemming from suspended sediment. Ironically, the principle source of sediment in surface water is cropland erosion (Brown et al., 1974; Magleby et al., 1989). Farm-related problems associated with sediment in irrigation water are reduced soil permeability, inability of seedlings to emerge through surface seals, increased costs of pumping and maintenance of irrigation systems. Sheet, rill, gully, streambank erosion, and streambank scouring all contribute to the sediment load in a river.

Sediment load depends on several factors. Among these are stream flow velocity, TDS concentration, water temperature, and rainfall intensity.

Streamflow Velocity

The kinetic energy of flowing water is described as the mass of water capable of doing work by virtue of its velocity:

$$E = \frac{1}{2} m v^2 \qquad \text{eqn 1}$$

where: E = kinetic energy (ergs)
m = mass of water (gm)
v = velocity (cm sec^{-1})

Stream flow velocity correlates directly with suspended sediment load though daily fluctuations in sediment load occur as a result of daily and seasonal fluctuations in streamflow such as snowmelt run-off or rainfall intensity (Leopold and Maddock, 1953; U.S.G.S., 1986) (Figure 2). Furthermore, during floods, larger land areas along stream banks are exposed to moving water, providing opportunity for additional soil particles to be picked up and suspended in the moving stream.

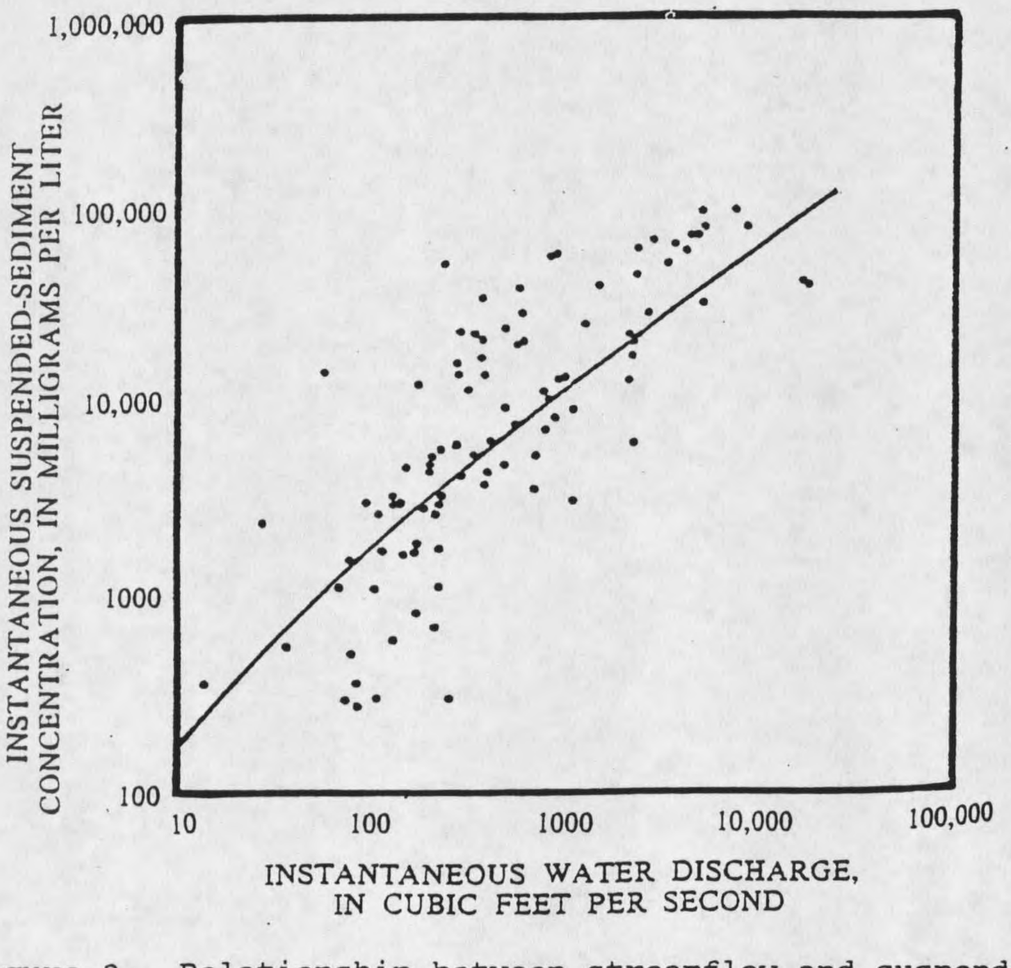

Figure 2. Relationship between streamflow and suspended sediment concentration for the Pwder River (from U.S.G.S., 1986).

TDS Concentration

TDS concentration has been used as an indication of salinity levels of irrigation water. TDS concentration is generally inversely proportional to discharge. This conclusion is supported by a U.S.G.S. (1986) hydrograph of Powder River stream-flow data plotted versus TDS concentration (Figure 3). High concentrations of dissolved solids result in a compression of the electrostatic double layer surrounding particles of suspended sediments. These particles subsequently join, forming flocs that settle out of the flowing system. thereby reducing sediment concentration.

Water Temperature

Water density and viscosity are directly related to water temperature and have a direct influence on the sediment load the water transports. Colby and Scott (1965) reported that as water temperature increases, the ability of the water to support suspended sediments decreases.

Rainfall Intensity

Soil erosion increases as rainfall intensity increases. However, this does not necessarily mean flowing water will carry more sediment following rain. According to Smerdon (1964), mean flow velocity decreases in the zone immediately surrounding raindrop penetration in a flowing water system due to a momentum exchange from flow to the raindrop-

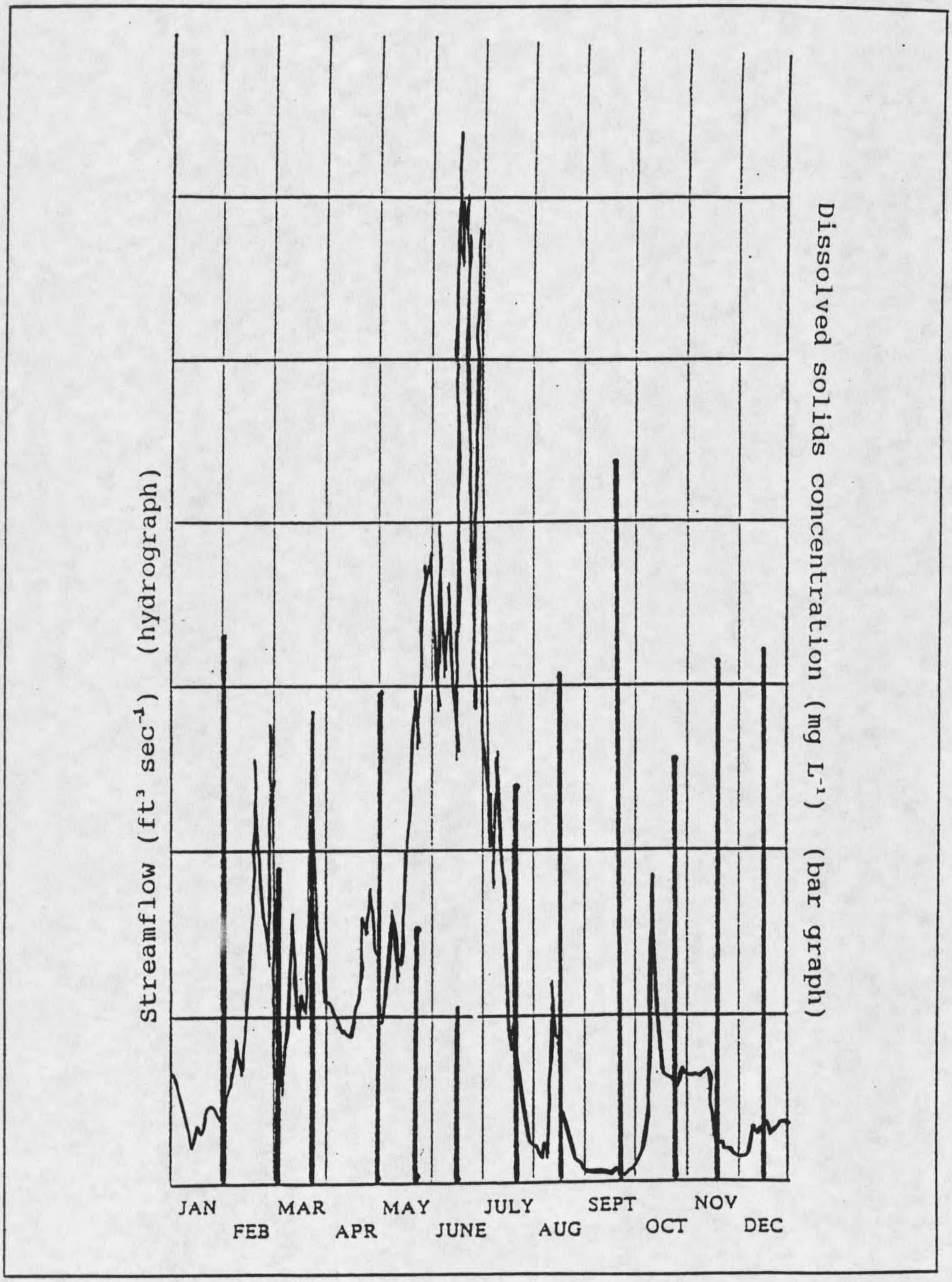

Figure 3. Relationship between Powder River streamflow and TDS near Arvada, Wyoming (from U.S.G.S., 1986).

affected zone. The result is a reduction in the ability of the water system to erode stream banks or to carry sediment. This effect is more important in smaller streams than in larger tributaries since the raindrop-affected area is relatively greater in smaller streams.

Sediment Characteristics

Fine sediments increase the viscosity of the stream system, thereby reducing the fall velocity of other sediments in the stream systems. Simons et al. (1963) found that the falling velocity of sand (0.47mm) decreased by 65% and 20%, respectively, when bentonite and kaolinite were the predominant suspended sediments. Bentonite is a common source of fine particle sediment in many western streams (Simons et al., 1963). Furthermore, suspended sediment increases the abrasive power of the flowing water to scour streambanks.

Sediment Transport and Deposition

Hjulstrom (1935) proposed the line of demarcation between sediment transport and deposition over a range of flow velocities and particle sizes shown in Figure 4. According to the diagram, loose fine sand (0.02-2 mm) is the easiest to erode. Larger sand particles (>2 mm) and silt and clay-size particles (<0.02 mm) are approximately equally prone to erosion. However, larger sand size particles are not easily transported, even at high velocities, while silt and clay particles, once in suspension, remain there even at the lowest velocity range shown. Partheniades (1965) found that the critical velocity (the velocity above which all clay stays in suspension and

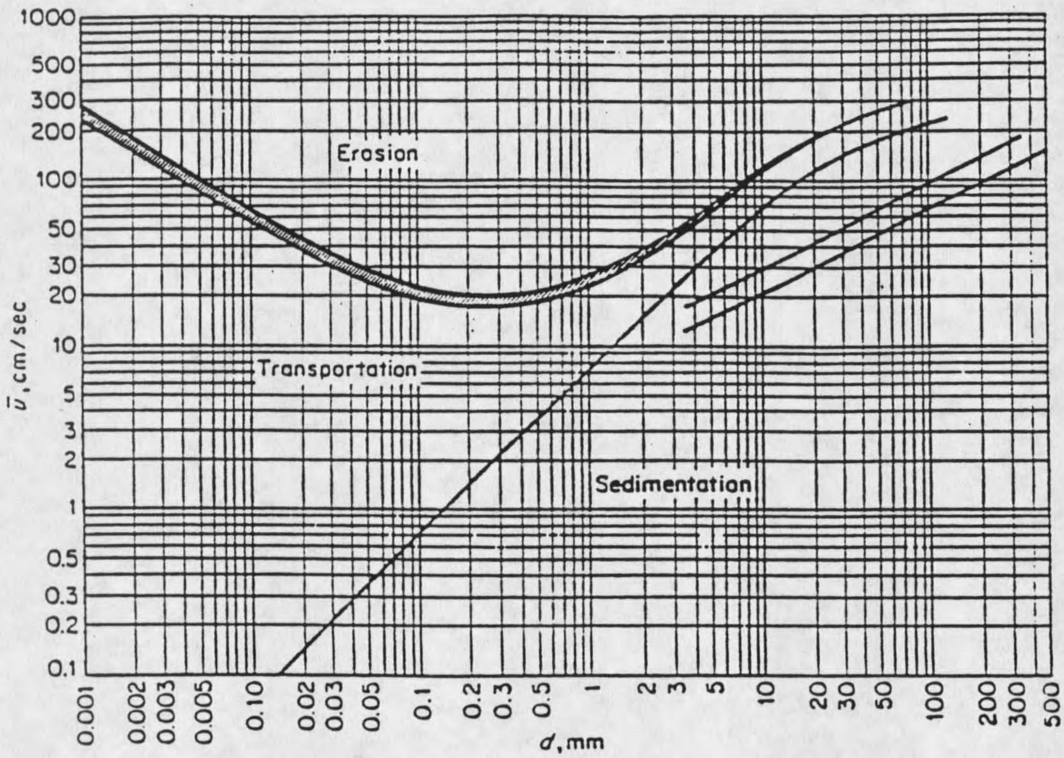

Figure 4. Erosion-deposition criteria for uniform particles (from Hjulstrom, 1935).

below which all clay is deposited) in San Fransisco Bay is about 0.5 sec^{-1} (~15 cm sec^{-1}); however, Bell (1942) suggests a flow rate of only 3cm sec^{-1} is enough to keep particles less than 20 μ in suspension.

The U.S.D.A. (1950) studied the effects of diverting sediment-laden runoff water onto range and cropland in New Mexico. Selected results are presented in Table 1. The amount of deposited sediment decreased with distance from the water inlet; the extent of deposition was dependent on the configuration of the water spreading pattern. Deposition of sediment "lightened soil texture in upper reaches" ... and "just below lightened areas the texture became heavier." Clay was the prevailing soil texture in the entire study area prior to flooding. After 8 years of repeated flooding, the textural class of the upper 125 feet of the flooded area was transformed to a sandy loam; 650 feet below the water inlet the textural class was transformed to sandy clay loam; 1000 feet below the water inlet the textural class was transformed to clay loam. At 2000 feet, the original clay textural class remained unchanged, although sand content increased by six percent.

On a set of plots served by a ditch, in the same study area, sand was deposited on the first 2000 feet of ditch. As a result, flooded areas recieved heavy-textured sediment deposits. Sand percent decreased an average of 37%, while clay percent increased an average of 38% on all plots over a nine year period. Apparently, deposition of the clay fraction occurs on fringes of irrigation water infiltration and along the retreating edge of the irrigation water advance.

Salinity

Soil and water are considered to be saline when the salt concentration is sufficiently high to become harmful to plants, either directly due to toxicity or indirectly due to osmotic stress. The definition of saline soil and saline

	Irrigated (Sediment Laden Water)			Non-Irrigated		
Year	Sand	Silt	Clay	Sand	Silt	Clay
1938	67.98	13.68	18.34	57.37	18.13	24.49
1939	50.63	19.83	18.34	59.51	18.78	24.49
1940	29.23	27.88	29.54	62.03	16.37	22.55
1941	13.53	35.40	42.87	61.50	16.95	21.58
1942	32.03	22.73	50.96	61.78	16.37	21.53
1943	37.00	24.50	45.22	61.53	16.92	21.83

Table 1. Selected data comparing changes in textural composition of surface soil on irrigated vs. non-irrigated plots (from U.S.D.A., 1950).

water is not rigid, but is determined by the sensitivity of the plant or crop in question or the intended use of the soil or water. All soils and all natural waters contain some dissolved salts.

Many researchers have reported soil EC increases with prolonged irrigation in western states (Rhoades, 1972; Grismer, 1990; Thellier et al., 1990). Chemistry of irrigated soil may reflect that of the irrigation water in as few as one to three years after the initiation of irrigation (Schafer, 1983). Many irrigation waters in the western states are moderately to highly saline. However, irrigation water does not need to be saline to cause an increase in soil EC. Even "clean" irrigation water will raise soil EC as a result of inadequate leaching, mineral dissolution, or capillary rise of deeper, more saline water towards the surface.

Salt concentration of irrigation water and of the soil saturation extract is commonly inferred from the EC of the water sample or soil extract. The EC of a solution is proportional to the solution salt concentration. Concentration of salts in water is frequently expressed as TDS in mg L^{-1}. The expression TDS = 640 * EC (dSm^{-1}) describes a generalized relationship between EC and TDS (U.S. Salinity Laboratory Staff, 1969), although the proportionality should be verified for different water sources. For Powder River water, TDS = 690 * EC (Gallagher, 1986). While some salt is necessary in the soil solution to maintain soil aggregate stability, excessively high salt concentrations in soil solutions are harmful to plants.

Two factors are responsible for negative plant responses to high salt concentrations (James et al., 1982): i) the osmotic effect, in which high concentrations of salt reduce soil solution osmotic potential and subsequently inhibit the ability of plants to absorb water, and ii) the specific ion effect, in which an accumulation of toxic ions in solution (usually Na, chloride (Cl), or boron (B)) occurs as salts concentrate in plants.

Primary mechanisms by which soil solution EC increases are evapotranspiration of applied irrigation water (Rhoades, 1972) and inadequate drainage (van Schilfgaarde et al., 1973). However, with proper irrigation management, a salt balance in the soil can be maintained. Salt balance occurs when enough water is applied to satisfy crop needs, to accommodate evaporation, and to displace salts below the root zone. Water that passes through the root zone is called the leaching fraction and is determined on the basis of the salt load of the applied water and that of the drainage water. Soils with low intake rates are often insufficiently leached (Lonkerd et al., 1979) because of the slow rate of transmission of water through the profile.

Sodicity

Sodium accumulation frequently results in destruction of physical structure and aggregate stability of soil, resulting in a reduction in hydraulic conductivity (K). The source of Na may be weathering of primary rocks, marine sediment deposits such as shales or sandstones, or sodic irrigation water.

Exchangeable sodium percent (ESP), which is the degree of saturation of the soil exchange complex with Na, is the commonly used measure of Na hazard in soil. ESP is defined in equation 2 as:

$$ESP = \frac{NaX}{CEC} * 100 \qquad \text{eqn 2}$$

where X refers to the soil exchange complex, Na is the concentration of adsorbed Na, and CEC is the cation exchange capacity in mg per 100 grams of soil.

SAR is typically used to approximate soil ESP because of the relative ease of analysis required to define SAR. SAR is derived from analysis of the soil saturated extract. The Na hazard of irrigation water, also determined by its SAR, is measured directly.

The equation describing SAR was developed by Gapon, based on the following exchange reaction:

$$Ca_{\frac{1}{2}}X + Na^{+} = NaX + \frac{1}{2}Ca^{++} \qquad \text{eqn 3}$$

At equilibrium, the Gapon selectivity coefficient (K_g) is written:

$$K_g = \frac{[Ca^{++}]^{1/2} NaX}{[Na^{+}]\, CaX} \qquad \text{eqn 4}$$

Soluble ion concentrations are expressed in mmoles per liter (mmL^{-1}) and exchangeable ion concentrations are in milliequivalents (meq) per 100 grams of soil. The ratio of exchangeable Na to exchangeable Ca is written:

$$\frac{NaX}{CaX} = K_g \frac{[Na^+]}{[Ca^{++}]^{1/2}} \qquad \text{eqn 5}$$

The ratio of NaX/CaX is a unitless measure of the exchangeable Na ratio (ESR) as shown in equation 6.

$$\frac{ESP}{100 - ESP} = ESR \qquad \text{eqn 6}$$

Assuming that Ca and Mg replace Na on the exchange complex with equal strength, the ratio of Na to Ca and Mg is the SAR. When cation concentrations are converted to milliequivalents per liter (meq L^{-1}), SAR can be calculated as follows:

$$SAR = \frac{[Na^+]}{\sqrt{\frac{[Ca^{++} + Mg^{++}]}{2}}} \qquad \text{eqn 7}$$

Correspondingly, the Gapon equation states:

$$\frac{ESP}{100 - ESP} = K_g SAR \qquad \text{eqn 8}$$

Analysis of fifty-nine soils of the western United States revealed that $K_g = 0.01475$ (U.S. Salinity Laboratory Staff, 1969).

Two assumptions apply to use of the Gapon equation for determination of Na hazard: i) Ca and Mg replace Na equally, and ii) a single K_g value represents soils with different clay mineralogies. In fact, K_g varies inversely with the Ca to Mg ratio (Palawi and Gandhi, 1976). This Ca to Mg relationship may be important in cases where soils are derived from Mg-rich parent materials. Shainberg et al. (1980) also found that K_g depends on the composition of the exchange phase. Furthermore, when mineralogy of a soil is dominated by a single type of clay, the recommended Kg value may not be adequate. According to Palawi and Gandhi (1976), "If one were to calculate ESP of a soil on the basis of the average equation, it would under-predict ESP of the light textured soil and overpredict that of a heavy textured soil at a particular SAR."

Where bicarbonate (HCO3) concentrations are significant, Ca ions precipitate according to the equation:

$$Ca^{++} + 2HCO_3^- = CaCo_3 + H_2O + CO_2 \qquad \text{eqn 9}$$

Precipitation of Ca++ effectively raises the relative Na concentration in solution (Wilcox et al, 1954). In order to reflect this reaction, an adjusted SAR equation (SARadj) was developed by the U.S. Salinity Laboratory Staff (1969).

The SARadj values are often two to three times greater than the standard calculation would predict. Several researchers have reported that the SARadj overstates the potential for precipitation of Ca. Saurez (1981) proposed a new method for calculating SAR, adjusted for HCO3. SAR values derived from the Saurez approach are quite similar to the predicted values (eqn 8) and are considered to be a better reflection of true Na hazard (Westcot and Ayers, 1984; Saskatchewan Water Corps., 1989). Comparison between predicted and calculated SAR values of different irrigation waters is presented in Table 2.

Water Source	SAR*	SARadj**	SARadj***
Rivers:			
S.Saskatchewan	0.53	1.03	0.58
Qu'Appelle	3.71	10.02	4.64
Lagoons:			
Swift Current	4.60	13.34	5.56
Govan	5.86	17.60	7.06
Groundwater:			
Tyner Valley	13.63	32.70	15.86
Hatfield	15.67	40.00	18.24

* Standard SAR calculation U.S. Salinity Laboratory Staff, (1969)
** Adj. SAR, U.S. Salinity Laboratory Staff, (1969)
*** Adj. SAR, Saurez, (1981) and Westcot and Ayers, (1984)

Table 2. Comparison of SAR and adjusted SAR values for selected Canadian waters (from Saskatchewan Water Corps., 1989).

Saturated Hydraulic Conductivity

Darcy's Law is regarded as the fundamental law describing flow of water through soil. It states:

$$v = \frac{Q}{At} = -K \nabla H \qquad \text{eqn 10}$$

where velocity flux (v) is equal to the volume of water (Q), flowing through a cross-sectional area (A), per unit time (t), ∇H is the hydraulic gradient, and K is a proportionality constant. The driving force, ∇H, is the hydraulic potential drop per unit distance in the direction of flow. Hydraulic potential (H) is the sum of a pressure potential (h) and a gravitational potential (z). In a horizontal column, the gravitational potential is zero and flow occurs in response to the pressure potential in the direction of decreasing potential (Figure 5a).

In a vertical column, flow is due to gravitational potential and pressure potential. The gravitational potential (z) is determined by the height of a point in relation to a reference plane. In Figure 5b, the reference plane (where g=0) is the bottom of the column. The pressure potential is determined by the height of the water column above the point of interest. Darcy's Law restated for a saturated vertical column is written:

$$\frac{Q}{At} = -K\frac{h}{L} \qquad \text{eqn 11}$$

where K is in centimeters per second and the hydraulic gradient (hL^{-1}) is the ratio of pressure potential to sample length (L), which is also gravitational potential in this case.

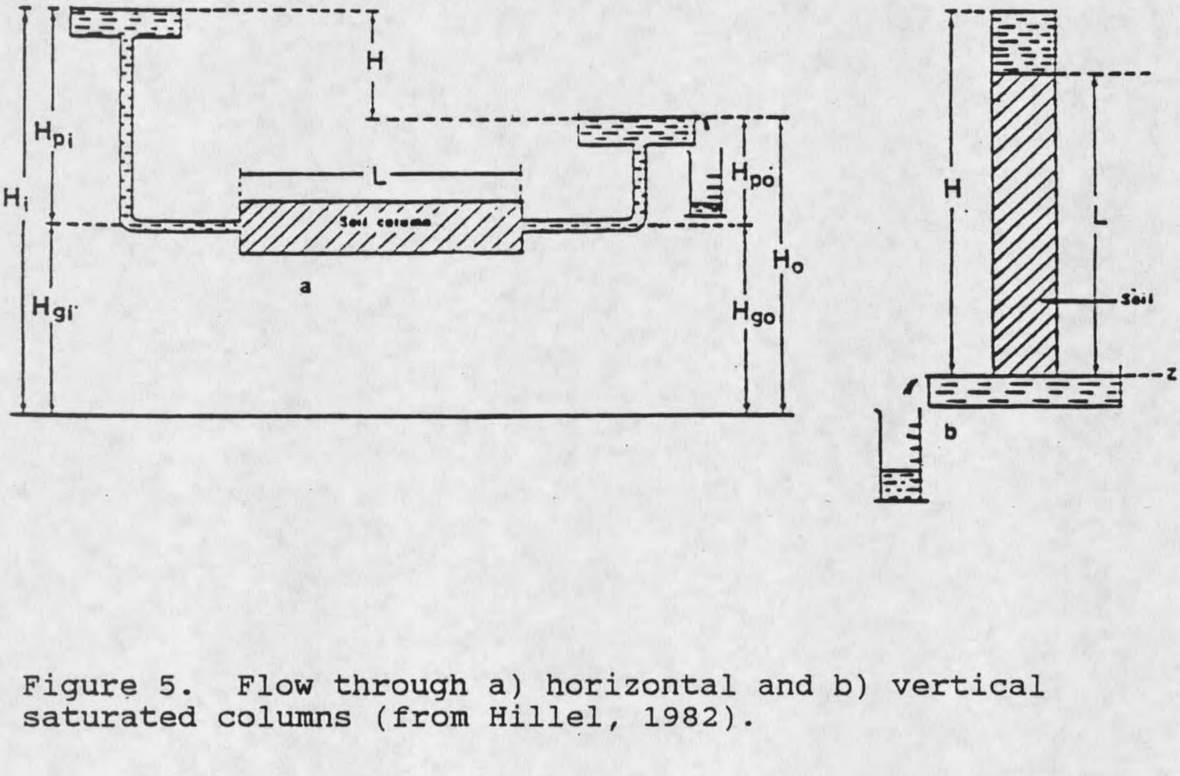

Figure 5. Flow through a) horizontal and b) vertical saturated columns (from Hillel, 1982).

Hydraulic conductivity consists of a permeability factor (k) and a fluid factor:

$$K = k\frac{\rho g}{\eta} \qquad \text{eqn 12}$$

The fluid factor accounts for solution viscosity (η), solution density (ρ), and gravitational forces (g); both η and ρ are temperature-dependent variables. Under laboratory conditions (and even in conditions common to field applications), temperature ranges are sufficiently small to render variations in solution density and viscosity negligible. Permeability describes pore geometry, which consists of pore radius, pore size distribution, tortuosity, and total porosity. Soil texture and structure are the principal determinants of soil geometry. Saturated hydraulic conductivity represents an integration of the differential in flow velocity throughout the entire range of pore sizes and configurations within the soil (Figure 6).

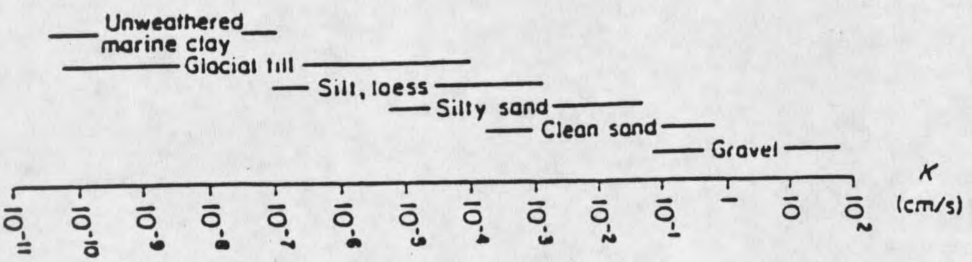

Figure 6. Range of K values for various earth surface materials (adapted from Freeze and Cherry, 1979).

In ideal conditions, intrinsic permeability of a porous medium remains constant with time despite properties of the flowing solution. In reality, chemical properties of the soil solution change the pore geometry, particularly when soil is dominated by 2:1 layer silicates. The discrepency between intrinsic permeability and K can be explained by the fact that permeability is derived from the Kozeny-Carmen equation which ignores chemical factors. The Kozeny-Carmen equation states (Yaron et al., eds., 1973):

$$k = \frac{\theta^3}{mt^2 S_0^2 (1-\theta)^2} \qquad \text{eqn 13}$$

where: θ = porosity
m = a pore shape factor (~2.5)
t = tortuosity ($\sim 2^{1/2}$) and
S_o = specific area per unit volume of particles

In the following section some dynamic relationships between soil physical properties of clay-dominated soil, electrolyte composition and concentration of the soil solution, and K will be described.

The Hydraulic Conductivity Connection

Water quality characteristics are intimately related to soil chemical and physical properties. The ratio of EC to SAR of the soil solution regulates K and infiltration, two components of permeability. Classification of soils based on EC and SAR levels of saturated soil extract are presented in Table 3.

Irrigation water is also catagorized based on EC and sodicity hazard (Figure 7). In addition, the need to consider soil texture when developing irrigation water

Classification	EC	SAR
Normal	<2	<15
Saline	>2	<15
Sodic	<2	>15
Saline-Sodic	>2	>15

Table 3. Classification of soils according to EC and SAR.

guidelines is widely recognized. Park and O'Conner (1980) suggest that when saline-sodic water is the main irrigation water source and is supplemented by rain, i) all waters can be used on very sandy soils; ii) no saline-sodic water should be used on fine textured soils; and iii) slightly, but not highly, saline-sodic water can be used on medium textured soils.

Hydraulic conductivity may be drastically reduced when leached with irrigation water which has low EC and high SAR (McNeal B.L. and N.T. Coleman, 1966; U.S. Salinity Laboratory Staff, 1969; Pupinsky and Shainberg, 1979; Abu-Sharrar et al., 1987; Yousaf et al., 1987). Conversely, K can be maintained even under conditions of high SAR irrigation water if the soil solution critical or threshhold electrolyte concentration is maintained above specified critical threshold levels (Quirk, 1957).

Aggregate swelling and aggregate dispersion are responsible for reducing K. Dispersion appears to play the primary role in reducing K under low EC-high SAR conditions

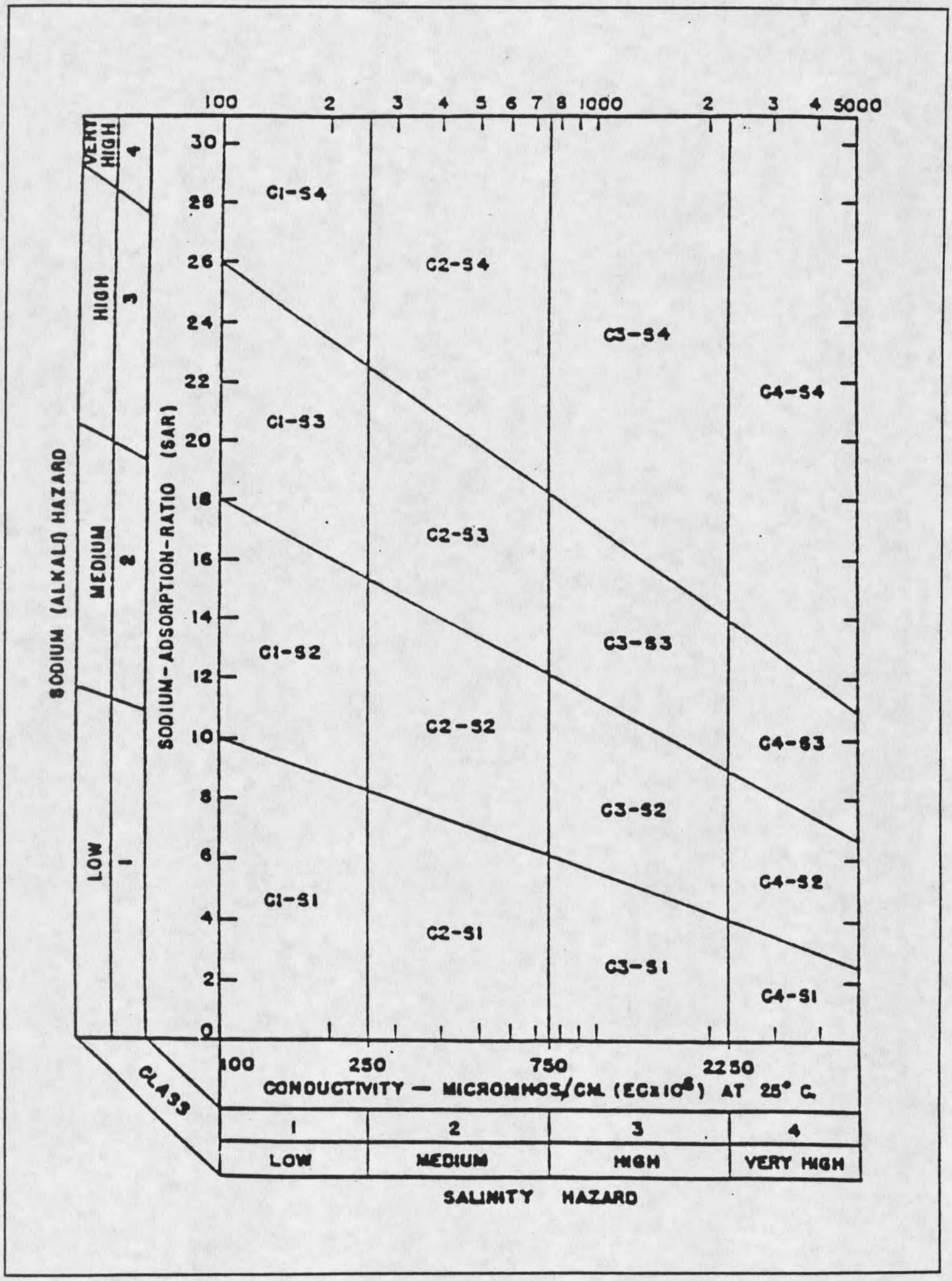

Figure 7. Suggested classification of irrigation waters (from U.S. Salinity Laboratory Staff, 1969).

(when ESP is 10-20 or less and the electrolyte level is less than 10 meq L^{-1})(Shainberg and Caiserman, 1971; Frenkel et al., 1978: Pupinsky and Shainberg, 1979; Yousaf et al., 1987). Dispersion causes clay particles to migrate and lodge in interstitial pores, thereby plugging pore pathways. Interlayer swelling is responsible for reducing K at extremely high SAR levels (SAR>25) in 2:1 clay silicates. This swelling reduces effective pore size (McNeal and Coleman, 1966; Pupinsky and Shainberg, 1979; Shainberg and Caiserman, 1971). When SAR levels exceed 30-40, swelling pressure weakens interlayer bonds and disposes clay to further dispersion and complete loss of structure (Fenhendler et al., 1974). Slaking, or breakdown of soil aggregates, is more important than dispersion in reducing K when soils leached with high SAR-low EC waters are subsequently leached with distilled water (Abu-Sherrar et al., 1987). Aggregate dispersion and pore plugging lead to crust formation and surface sealing following rainstorms.

Dispersion occurs prior to swelling in 2:1 layer silicates. Ca-saturated clay particles generally form small, discrete aggregates. Effective surface area of these aggregates is much less than that of the total of the individual clay platelettes. With initial increases in soil solution SAR, Na is adsorbed to external aggregate surfaces, increasing thickness of the diffuse double layer. Repulsive forces that develop cause dispersion of aggregates. Ca remains in the interlayer positions, thus preventing swelling and loss of aggregate integrity. Further increases in SAR cause displacement of some of the interlayer Ca and subsequent replacement with Na. The resultant increase in interlayer ion concentration decreases osmotic potential. Soil solution flowing into the interlayer spaces then results in swelling and, in extremely sodic conditions, disintegration of aggregates occurs (Frenkel et al., 1978).

Several researchers have attempted to predict K under a variety of circumstances. Jayawardane and Blackwell (1991) found a strong correlation between predicted and measured K for various equivalent salt solutions. Equivalent salt solutions are defined as solutions containing different combinations of EC and SAR that produce a fixed amount of swelling (loss of K) in a given soil. Jayawardane and Blackwell (1991) propose that equivalent salt solutions for different soils can provide a satisfactory prediction of changes in K. Yousaf et al. (1987) demonstrated a threshold relationship between EC, SAR and clay content such that a sharp decline in K occurs with small amounts of clay dispersion (4-10 g kg^{-1} soil). Yousaf et al. (1987) suggest their method of measuring clay dispersion can be used for predicting permeability problems associated with sodic soils and waters.

CHAPTER 3

METHODS AND MATERIALS

Two studies were conducted. The objective of Study I was to determine if a relationship exists between sediment concentration in irrigation water and K_{sat}. The objective of Study II was to determine if sediment deposition from long-term irrigation promotes variation in surface soil texture.

The Soils

Soil for both studies was collected from adjacent sites within a single soil mapping unit bordering the Powder River, at the Prairie-Custer County line (Figure 8). The soil is characterized as the Glendive Series (Steve Van Faussen, SCS Soils Scientist, personal communication), a deep, nearly level soil derived from alluvium over stratified sedimentary bedrock. The surface soil consists of clay loam, silty clay loam, or loam ranging from 30 to 80 centimeters thick and underlaid by stratified fine sandy loam and loamy fine sand.

The selection of this soil was practical for the following reasons:

i. The Glendive soil is a benchmark series widely

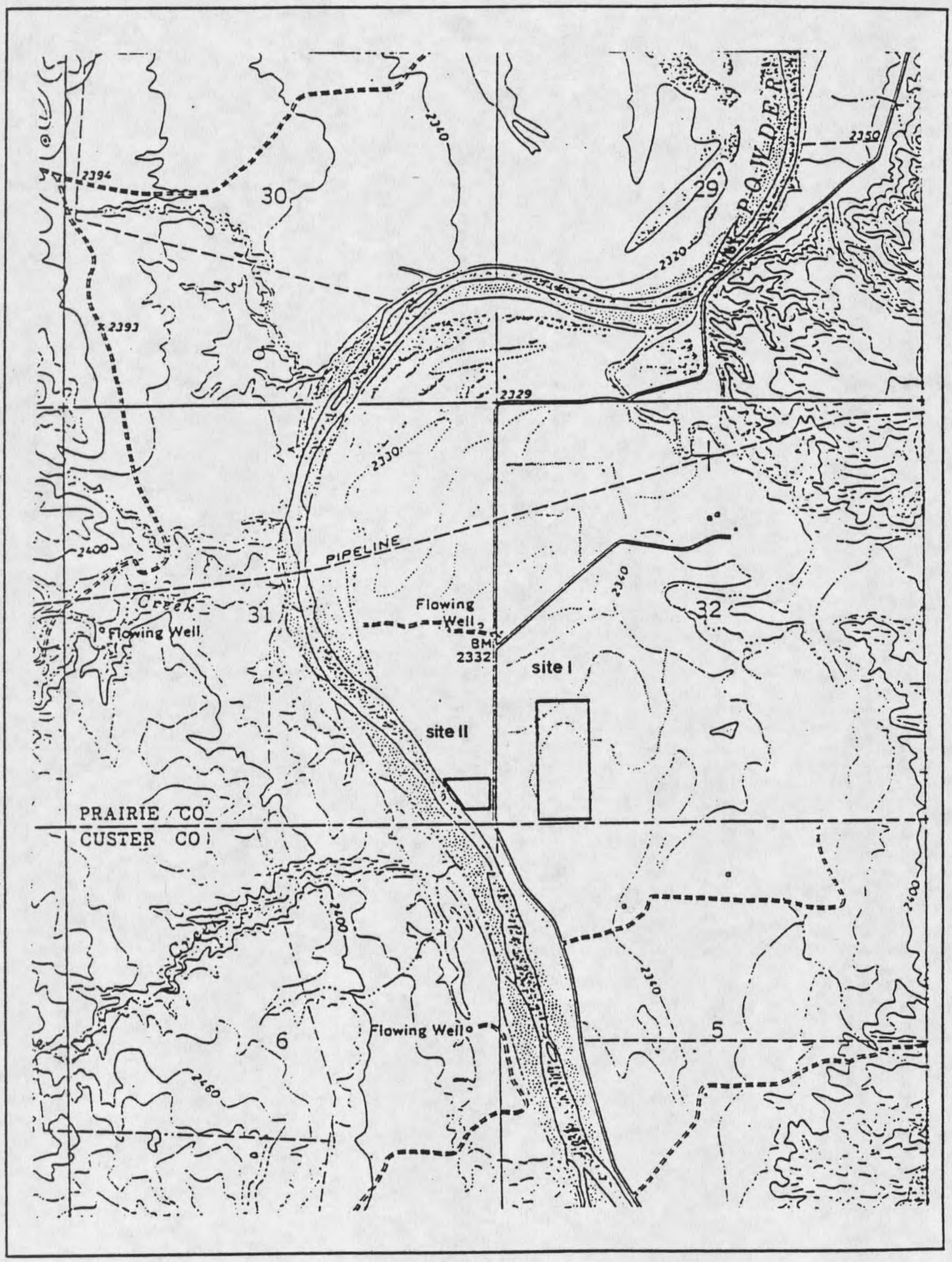

Figure 8. Map of the Powder River study area (U.S.G.S. 1964. Spring Creek Quad, 7.5 minute series topographic map).

distributed in Montana, Wyoming, Colorado, North and South Dakota and is most often found under irrigated conditions. Knowledge gained from studies on benchmark series can be applied to other soils with similar properties (Montagne et al., 1982).

ii. Suspended sediment is of considerable importance to irrigators who modify their management practices based on sediment load in the water.

iii. Concentration of suspended sediment in the irrigation water source (the Powder River) is well above the average of other northwest and plains states rivers and irrigation water supplies (U.S.G.S., 1986), thus, the results of this study may serve as an 'accelerated' model for trends in other irrigation sources carrying lower suspended sediment concentrations.

Study I: Saturated Hydraulic Conductivity (K_{sat})

Irrigation water regimes representing the range in salinity and sodicity of irrigation water previously described in Table 3 were used to measure K_{sat} . It is well documented that K has a well documented response to EC, SAR, and EC-SAR interactions. On the other hand, the effect of sediment concentration on K is not well documented.

Constant head K_{sat} was measured on packed cores of ground soil obtained from the study site. The method used to assess K was recommended by McIntyre and Loveday (1974) for the following reasons:

> "Measurement of hydraulic conductivity under a positive head is often made on cores or packed columns of ground soil as being the best practical alternative (to field measurement). The data produced are useful in the comparative sense and in particular, ground soil may perhaps be reasonably representative of the actual condition of tilled surface soils. For most soils finer in texture than sandy loam, the saturated hydraulic conductivies will rate in the same order as the unsaturated values at which significant movement of water occurs in the field."

McIntyre and Loveday further note that conductivity in undisturbed cores may be altered by up to two orders of magnitude. These disparities are caused by compaction or rearrangement of pore space that can not be avoided in field collection (Rogers and Carter, 1987). Conversely, packed cores can be made homogenous, thus providing reproducible values, if thoroughly mixed and prepared using standardized methods.

<u>Soil and Sediment Sampling</u>

The systematic sampling procedure described by Petersen and Calvin (1986) was used to collect discrete units of bulk soil and bulk sediment from transects on six adjacent graded border panels 90 feet wide and 1,000 feet long. The field from which samples were collected was in a three year old stand of alfalfa at the time of sampling.

Soil samples were collected from the top 15 centimeters of the profile. The surface ½ centimeter of each sample location was reserved as the sediment portion of the sample. This depth was a randomly selected criterion to separate irrigation-supplied sediment from in-situ soil.

The soil portion was dried, ground, and packed into sections of PVC pipe to create the soil cores employed in the measurement of K_{sat}. The sediment sample was added to irrigation water solutions to achieve suspended sediment concentrations required for the various treatments. Particle size analyses were completed for the soil and sediment samples. Results (Table 4) reveal that the sediment portion contained less sand and more clay than the soil portion of each sample.

Sample	Sand 0.05mm	Silt 0.002-0.05mm	Clay <0.002mm
	Percent (g/g * 100)		
Soil	48.5	31.1	20.1
Sediment	20.1	28.6	51.3

Table 4. Particle size distribution of bulk soil and sediment used in K_{sat} study (Study I).

<u>Soil and Sediment Sample Preparation</u>

Bulk sediment was rinsed three times with distilled water in order to remove free ions. Each rinse volume of distilled water was double the volume of the bulk sediment. The sediment was then dried, ground, and thoroughly mixed.

Bulk soil was passed through a 2mm sieve, and placed in each soil column according to the method described by McIntyre and Loveday (1974). This method was used to insure the entire particle size spectrum was included and well mixed in each sample. One hundred forty five grams of soil were measured into each cylinder and packed by sixty seconds of high velocity mechanical vibration. Average bulk density of the soil cores was 1.64 gcm^{-3}.

Solution Chemistry Preparation

Four irrigation water solutions were prepared, which represented the four EC/SAR combinations presented in Table 5. The GEOCHEM model was used to calculate amounts of various salts required to achieve the salinity and sodicity levels desired while preventing oversaturation with respect to CO_3 and SO_4 salts (Table 6).

SAR	EC ($dS\ m^{-1}$)	
	0.5	5.0
1	WQ 1	WQ 3
15	WQ 2	WQ 4

Table 5. EC and SAR combinations used to create water quality categories for irrigation solutions for K_{sat} study (Study I).

GEOCHEM is an aqueous speciation model that calculates ion activity coefficients and predicts complex formation. (Page, 1980)

Treatments

Sediment was added to each of the bulk solutions of the water qualities described in Table 5 to create irrigation waters with concentrations of 20, 2,000, and 20,000 mg of sediment per L of irrigation water, as shown in Table 7. These sediment concentrations reflect the annual range of suspended sediment in the Powder River (Gallagher, 1986; U.S.G.S., 1986).

Constituent	** WQ1	** WQ2	** WQ3	** WQ4
* Na^+	1.35	4.80	5.00	24.63
* Ca^{++}	1.71	0.55	27.50	12.40
* Mg^{++}	1.81	0.10	27.50	12.50
* HCO_{3-}	1.35	4.80	2.50	12.50
* $SO_4^{=}$	2.62	0.55	32.50	36.76
* Cl^-	1.53	0.25	13.75	6.20
EC	0.55	0.40	4.35	4.57
SAR	1.04	17.50	2.85	14.47
pH	7.4	7.6	8.1	8.2

* Ions expressed in meq L^{-1}
** Water quality treatments with respect to EC and SAR

Table 6. Constituent composition and selected water quality parameters of treatment solutions used in K_{sat} study.

SAR	EC (dS m^{-1})	
	0.5	5.0
	Sediment Concentration (mg L^{-1})	
1	20 2,000 20,000	20 2,000 20,000
15	20 2,000 20.000	20 2,000 20,000

Table 7. Irrigation water combinations (EC x SAR x sediment concentration) used in K_{sat} study.

Experimental Apparatus

The experimental set-up is presented in Figure 9. Cylinders were constructed from 5 cm diameter (L) thick-walled PVC pipes cut to 20 centimeter lengths. Thin cotton fabric and window screening were glued to the bottom of each column to provide support for the soil, to allow drainage of effluent, and to prevent loss of soil particles. Insides of the columns were scarified with a wire brush and coated with a thin layer of sand in order to reduce laminar flow along the edges of the soil cores. Cylinders containing the packed soil cores (a) were suspended over funnels with ring-stands. Treatment solution was maintained at a constant head (h) of 18 centimeters within the cylinders.

A flask containing the treatment solution supply (b) was placed on a magnetic stirrer (c) set at a speed such that all sediment was kept in suspension. The Erlenmeyer flask apparatus (d) provided the pressure necessary to maintain constant head in the soil cylinder.

Procedure for Measuring K_{sat}

Each soil core was saturated from the bottom with the appropriate treatment solution (Table 5) for a period of 12 hours prior to data collection. Coarse steel wool was placed gently on the soil surface to minimize disturbance to the surface of the soil core at the time irrigation water was introduced to the column. A constant head of 18

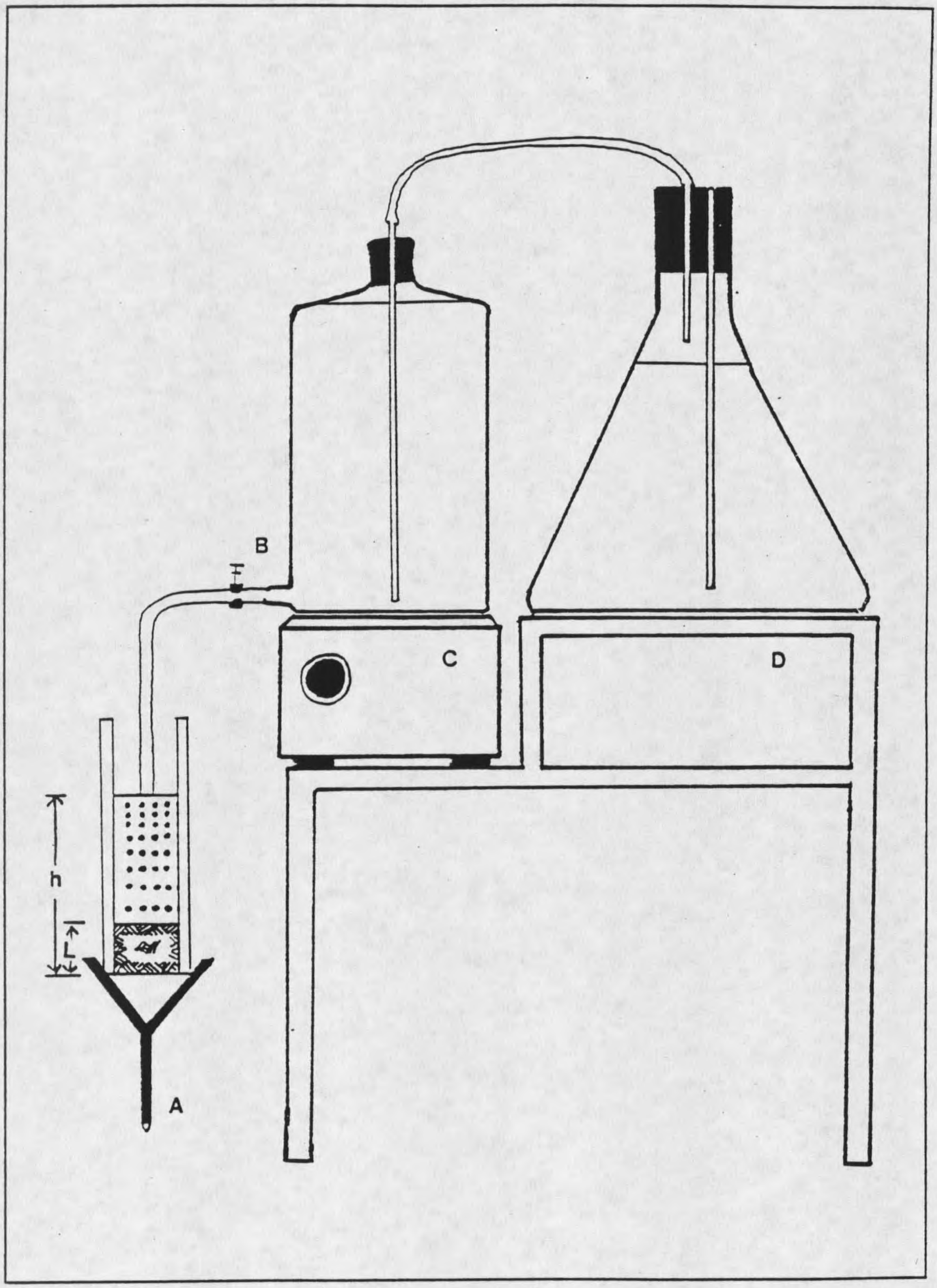

Figure 9. Experimental set-up for K_{sat} study.

centimeters of the appropriate irrigation water treatment was established. The steel wool was then removed and the solution level was adjusted as necessary by raising or lowering the cylinder. The amount of effluent produced was noted at frequent intervals for thirty minutes to assure that a constant and even flow had been established. Effluent collected during the initial thirty minutes was discarded. Following this calibration period, effluent volume was recorded at fifteen minute intervals, for 90 to 120 minutes. The constant head level of each column was adjusted as necessary following each recording. K_{sat} was calculated using Darcy's equation as follows:.

$$K_{sat} = \frac{Q}{At}\frac{L}{h} \qquad \text{eqn 14}$$

where: K_{sat} is expressed in cm per min (cm min^{-1})
Q = quantity of leachate (cm^3)
A = cross-sectional area of soil core (20.268 cm^2)
t = unit time (15 min)
L = length of soil core (5 cm)
h = hydraulic head (18 cm)

Statistical Analysis

The study was conducted as a completely randomized factorial with five replications of all twelve treatment combinations. The average K_{sat} for each column served as one replication.

Study II: Sediment Deposition Study

Soil textural variation across an irrigated plot reduces irrigation efficiency due to non-uniform penetration of irrigation water into the soil profile. On the Powder River, where irrigation water has high sediment concentrations, long term irrigation appears to create variation in soil textures across an irrigated plot. The purpose of the sediment deposition study was to determine if surface texture of land irrigated with Powder River water has been altered because of uneven sediment deposition.

Layout of Plots

Study II was conducted on the same site previously described (Figure 8). The two adjacent plots were within one soil mapping unit, and, except for irrigation history, appeared identical. One plot was established in a field that had been continuously irrigated for forty years (Bill Griffin, personal communication). The field had been planted to alfalfa four years prior to the study and there had been no cultivation during those four years. Presumably, any sediment that may have been deposited on the soil surface as a result of irrigation during that time period has remained relatively undisturbed. The second plot was a non-irrigated site that had no history of cultivation.

Identical plot layout and sampling schemes were conducted on the paired irrigated and non-irrigated plots

(Figure 10). The top of the plots was defined by the gated-pipe irrigation line. Plots 45 m by 60 m were divided into a grid of twelve blocks, each of which was 15 meters square.

Sampling Method

A template measuring 69 cm by 38 cm was placed in the center of each of the grid blocks. The entire surface one cm of soil was collected from within the template. Three sub-samples of this bulk sample were independently analysed for particle size distribution.

Particle Size Analysis

Particle size distribution was determined using the hydrometer method (Gee and Bauder, 1986). Forty gram soil samples were used.

Statistical Analysis

Observations were made on sets of paired experimental units. Paired units consisted of percent sand, percent silt, percent clay, and percent silt + clay on a mass basis, collected from four distance increments, on irrigated and non-irrigated treatment sites. Data was analysed using the MSU-STAT computer program developed by Lund (1991). Because the paired study sites were not randomly selected, bias is inherent to this study. For this reason, statistically determined differences may not necessarily be attributed to irrigation treatment; differences between the paired plots appears to be due solely irrigation treatment.

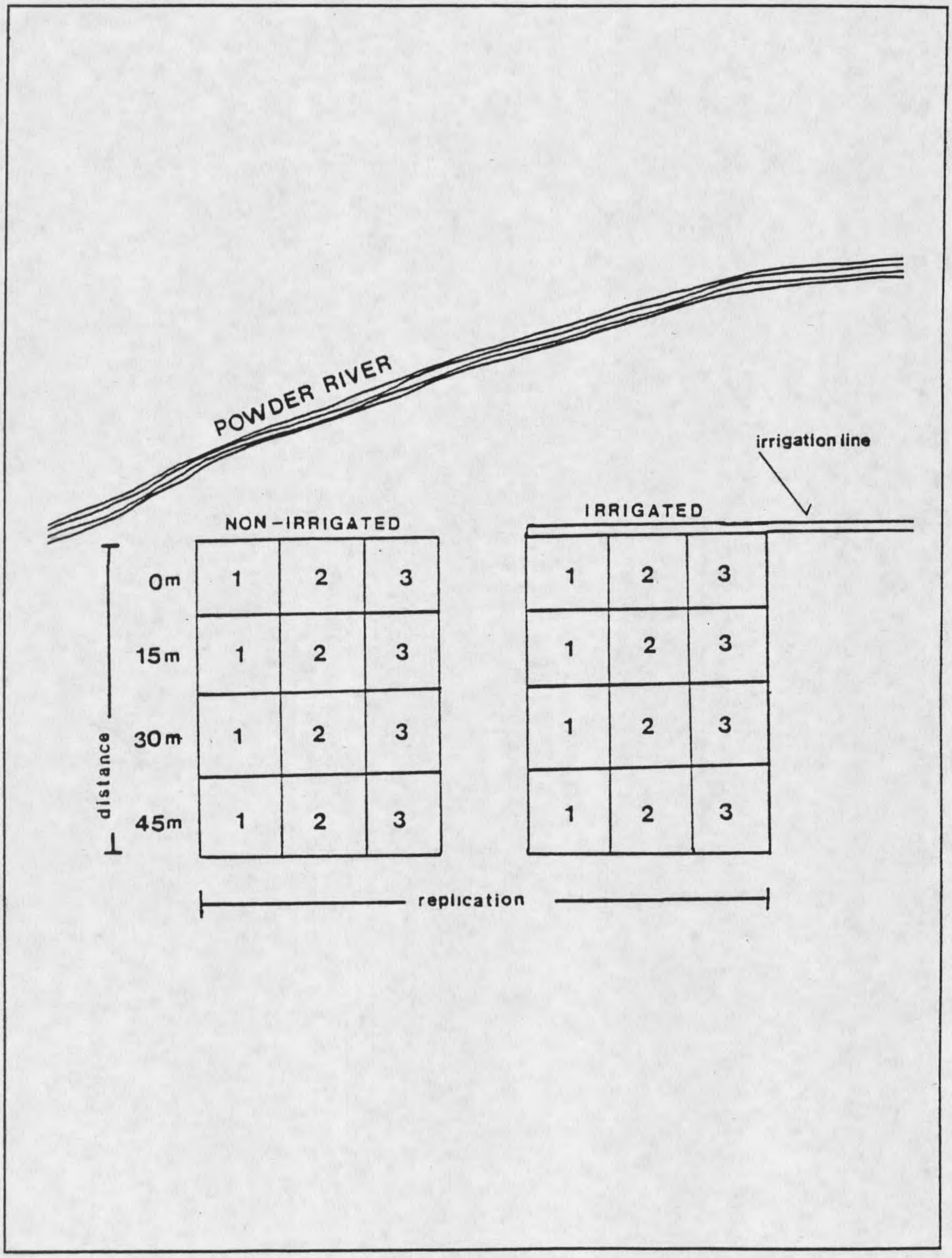

Figure 10. Layout of adjacent irrigated and non-irrigated plots from which sediment samples were collected for Study II.

CHAPTER 4

RESULTS AND DISCUSSION

Study I Results: Saturated Hydraulic Conductivity (K_{sat})

Results of ANOVA (Table 8) indicate that K_{sat} was significantly affected by EC and SAR of the irrigation water (p=0.01) and by the sediment concentration of applied water (p = 0.10).

Source	df	Mean Square	F-Value	P-Value
EC	1	$9.3*10^{-4}$	87.54^{***}	.0000
SAR	1	$3.2*10^{-4}$	30.32^{***}	.0000
EC*SAR	1	$7.5*10^{-4}$	70.94^{***}	.0000
SED	2	$4.0*10^{-5}$	3.81^{**}	.0292
EC*SED	2	$8.1*10^{-5}$	7.57^{***}	.0014
SAR*SED	2	$8.8*10^{-5}$	8.31^{***}	.0008
EC*SAR*SED	2	$4.3*10^{-5}$	4.06^{**}	.0236
RESIDUAL	48	$1.1*10^{-5}$		

*** Significant at $\alpha = 0.01$; ** at = 0.05
F(1:48) 0.01 = 7.1; F(2:48)0.01 = 5.0

Table 8. ANOVA for K_{sat} as a function of irrigation water quality and sediment concentration.

EC and SAR Effects

Mean K_{sat} was significantly greater ($2.5*10^{-3}$ cm min^{-1}) for soil columns leached with the high EC solutions than for soil columns leached with low EC solutions ($1.9*10^{-3}$ cm min^{-1}) (Figure 11). Similarly, K_{sat} in soil columns leached