Rainfall induced dispersion and hydraulic conductivity reduction under low SAR x EC combinations in smectite-dominated soils of eastern Montana

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Southeast Montana Soil Assessment

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Table of Contents

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Executive Summary

In September, 2006, an irrigator in the Tongue and Yellowstone (T&Y) irrigation district, headquartered in Miles City, MT, reported significant crop loss and irrigated alfalfa stand death following a sequence of events involving: irrigation, subsequent multiple days of rain and cool weather, followed by a substantial warming trend. Irrigation water applied to the field where crop loss and death was reported was sourced via the T&Y irrigation district, which secures water from the Tongue River. The Tongue River and quality of water in the river has been a subject of considerable debate since initiation of large-scale coalbed methane gas (coalbed natural gas; CBM/CBNG) industry development in the Powder River basin, which began in 1998. In an effort to ensure sustained integrity of the Tongue River to support irrigated agriculture, the Montana Department of Environmental Quality (DEQ) Board of Environment Review (BER) established in-stream water quality standards specific to salinity and sodicity in 2003. Further, in 2006, the BER established complimentary non-degradation provisions, applicable to the 2003 standards. Despite in-stream standards for the Tongue River, irrigators along the Tongue River and within the T&Y irrigation district have expressed concern about long-term impacts of CBM product water discharges on soil quality and sustainability of downstream irrigation practices. Correspondingly, there was concern expressed that the irrigated alfalfa stand death reported in 2006 by a T&Y district irrigator was consequent to water quality of the Tongue River during the 2006 irrigation season.

Shortly after the reported crop loss and stand death, two soil scientists (namely Steve VanFossen, Soil Scientist formerly with the USDA-NRCS Miles City office, now retired; and James W. Bauder, Extension Soil and Water Quality specialist with Montana State Univeristy and certified professional soil scientist, CPSS) independently reviewed the circumstances and prepared written opinions regarding the crop loss and stand death. Subsequently, in May, 2007 and at the invitation of the Montana DEQ, Montana State University Extension water quality specialist James W. Bauder submitted a proposal and engaged in a contract with Montana DEQ to conduct a comprehensive, objective, independent assessment of the conditions and circumstances contributory to the reported crop loss and stand death. Components of the assessment included:

- review of circumstances and quality of water of the Tongue River prior to the reported loss;
- extensive soil sampling and detailed physical and chemical analyses of samples collected from a variety of locations within and in proximity of the subject field (as evidenced from aerial photographs collected shortly after the reported incident);
- a series of controlled laboratory infiltration studies assessing the susceptibility of the subject soil materials to rainfall-induced dispersion following wetting with water having relatively low salinity and sodicity (comparable to water quality standards established by the Montana BER);
- a series of controlled laboratory infiltration studies assessing the susceptibility of the subject soil materials to rainfall-induced dispersion following wetting with water

having relatively low salinity and sodicity (comparable to water quality standards established by the Montana BER);

- inventory and assessment of irrigable, smectite-dominated clay soils along the Tongue River in Montana;
- extensive scientific literature review specific to circumstances of sodium and rainfall-induced dispersion of soil;
- assessment of the appropriateness and protectiveness of the Montana BER-adopted standards for salinity and sodicity of waters of the Tongue River, relative to sustainability of current irrigation practices with the T&Y and Tongue River water users association domain.

Inspection of USGS-reported water quality data for the Tongue River, particularly at the point of the T&Y diversion, approximately 12 miles south-southwest of Miles City, provided no overwhelming evidence of substantial or sustained increases in either salinity (expressed as EC-electrical conductivity) or sodicity (expressed as SAR-sodium adsorption ratio) of river water quality in 2006, and which were abnormal of historic in-stream circumstances. EC and SAR of the Tongue River at T&Y diversion in 2006 reflected in-stream increases between Tongue River reservoir and the diversion due to in-stream evapoconcentration, baseflow contributions to flow between Tongue River reservoir and T&Y diversion, and likely contributions of irrigation return flows. The assessment of no significant increases in either salinity or sodicity were further substantiated through reviews of independent reports by Osborne (accessible at http://bogc.dnrc.mt.gov/ CoalBedMeth.asp) and Dawson (through 2005, accessible at http://www.epa.gov/region8/water/ monitoring/TongueRiverReportDraftFinal11Jul2007.pdf).

Soil sample physical and chemical analyses, completed on 28 samples collected from 7 different locations within and in the vicinity of the subject field, resulted in characterization of a dominant clay fraction in all samples collected. All samples, representing depths of 0-12", classified as either clay, clay loam, or silty clay loam. Clay content ranged from 28 to 62 percent by weight. Additionally, the clay fraction of 14 samples (0-2" and 2-4") which were subjected to X-ray diffraction (XRD) analysis identified the overwhelmingly predominant clay fraction as smectite. With respect to abundance, the clays present in the samples are: smectite >> kaolinite > mica/ illite. Chemical characterization revealed saturated paste extract salinities (expressed as electrical conductivity, i.e., EC) ranging from 0.49 to 2.0 mmhos/cm, and progressively increasing with depth of sampling. Samples from two sites had sodium concentrations exceeding 1,000 mg/l in the 6-12" depth. Additionally, all samples had Ca:Mg ratios of approximately 4:1. SARs ranged from 0.31 to 5.06, while ESPs ranged from 5.51% to 33.73%. Nitrogen levels were (generally) high while phosphorus levels were (generally) low on all but two sites, one of which had exceptionally high phosphorus soil test levels. Three of the sites sampled clearly demonstrated inherently elevated salinity and sodicity levels, while all of the sites sampled demonstrated an inherently elevated risk of rainfall-induced dispersion, based on ESP values. Interestingly, but explainable, the relationship between SAR and ESP was not consistent with that reported in the scientific literature. This is believed to be an artifact of the lag in time between the occurrence of the stand loss and sampling. Additionally, the saturated paste extract SAR likely reflected circumstances consequent to irrigation and rainfall reasonably near to the time of sampling. It was concluded that ESP provided a better representation of dispersion potential/risk than did SAR.

Near-saturated hydraulic conductivity measurements of soil columns configured with samples from the 0-2" and 2-4" soil depths and with samples from the 0-12" depths **revealed** circumstances (in some, but not all, cases) of **significant decreases in hydraulic conductivity upon wetting – in the case of intermittent wetting with rainfall, intermittent wetting with low EC x low SAR water, or intermittent wetting with alternating qualities of water.**

In the first laboratory study, selected soil samples were intermittently dosed with water of EC 2.04 mmhos/cm x SAR 4.1 and 'true' rain water, during a 16-hour period of continuous measurement of hydraulic conductivity. The soil was first wetted with EC=2.04 mmhos/cm x SAR=4.1 water. This was followed by a 2.54 cm (equivalent depth) rain water event. Subsequently, four additional dosings with EC=2.04 mmhos/cm x SAR=4.1 were imposed. **Not all soils demonstrated reductions in hydraulic conductivity upon wetting with rain water, although all soils demonstrated progressive decreases in hydraulic conductivity upon repeated wetting, alternated with periods of drainage.** Site 3, a clay loam with 34-36% clay, and site 7, a clay with 44-48% clay, demonstrated the most apparent reductions in hydraulic conductivity upon wetting with rain water. SAR and EC of site 3 were relatively low, while ESP was considered moderate, averaging 7.3%. Coincidentally, SAR and EC of site 7 were comparable to that of site 3, as was the ESP, averaging 8.3%. The common characteristics of these sites appear to be the combination of relatively high cation exchange capacity (CEC) x low EC, low SAR, and only moderate ESP.

Based on this controlled laboratory study, it was concluded that: 1) intermittent wetting caused significant reductions in hydraulic conductivity, likely leading to prolonged periods of water-logging and anaerobic soil conditions; 2) the extent and occurrence of prolonged periods of water-logging was likely quite variable across the subject field, thus leading to the observed differences in plant response; 3) in four of seven soil materials studied, single saturating events with rain water resulted in significant decreases in subsequent hydraulic conductivity when measured with EC=2.04 mmhos/cm x SAR 4.1 water; 4) decreases in hydraulic conductivity appeared to be more a consequence of the event of wetting than a consequence of the quality of applied water, i.e., there was no overwhelming evidence that reductions in hydraulic conductivity (surrogate to infiltration) in the subject soils were more significant when wetting occurred with 'true' rainwater then when wetting occurred with low EC x low SAR water; 5) the protocol of this study did not allow for definitive determination that introduction of rain water events resulted in measured decreases in hydraulic conductivity (infiltration).

A second laboratory experiment consisted of a sequence of 9 consecutive wetting (dosing) events, each equivalent to a 2.54 cm (1-inch) equivalent depth wetting event. The first six events consisted of water having an EC of 1.37 mmhos/cm x SAR=2.8. The seventh event consisted of 'true' rain water, having an EC = 0.06 mmhos/cm x SAR = ND. The last two events were identical to the first six events. This protocol was applied independently to a 3.5 cm depth of soil from the 0-5 cm depth (0-2") of sites 1-5. The objective was to assess: 1) whether infiltration (as measured by hydraulic conductivity) was constant over repeated wetting events with low EC x low SAR water; 2) whether infiltration would change/decrease abnormally from the established pattern, once rain water was introduced; and 3) whether, after the introduction of rain water, infiltration would decrease significantly.

In all cases, infiltration (measured as flow-through volume per unit time) decreased following the introduction of rain water. However, in all cases, infiltration also decreased between the second wetting event with EC=1.37 mmhos/cm x SAR=2.8 and the wetting event (#6) immediately preceding dosing with rain water, even though water quality was not altered between events 2 and 6. Additionally, infiltration decreased between events 6 and 7 (the introduction of rain water) at a rate consistent with the reductions preceding the addition of rain water, and at a consistent rate after the introduction of rain water. These data lead to the conclusion that **single rain fall events of the magnitude of this study did not appear to result in abnormally significant decreases in hydraulic conductivity or infiltration, when applied to saturated soils which had been previously wetted with relatively low EC x low SAR water.**

A third laboratory study was conducted using soil from the 0-2”, 2-4”, 4-6”, and 6-12” sampling depths of selected sites. A layer of 1.8 cm depth (loose, 10 mm sieved) 6-12” soil was placed in the bottom of the infiltration cylinder. Placed on top of this in sequence were: 1.8 cm depth of 4-6” and 1.8 cm depth of 2-4” soil. On top of this was placed a 1 cm depth of 0-2” soil. PR water with EC=1.37 dS/m, SAR=2.8 (U.S.G.S. Moorhead station, water sourced directly from Powder River immediately downstream of gauging station, 5/15/2008) was applied at a rate of 0.58 cm equivalent depth/minute for four minutes. Following the 20-minute equilibration period, a volume of 181 cc of PR water (equivalent depth = 2.54 cm) was applied to the surface of the soil in the infiltration cylinder. Once infiltration/saturated flow-drainage had ceased, an additional 181 cc of PR water was applied to the surface of the infiltration column, using procedure identical to that for the initial dosing with PR water. Once infiltration/saturated flow-drainage had ceased, 181 cc of ‘true’ rainwater was applied to the surface of the infiltration column, using procedure identical to that for the initial dosing with PR water. The process was then repeated a fourth and fifth time, using two sequential doses of 181 cc PR water, each applied by the same process as previously described. Infiltration/drainage rate was measured continuously for the duration of the experiment. This experiment was completed for selected sites (1, 2, 4, 5, 7).

Upon completion of this experiment, the entire experiment (including construction of a new infiltration column) was repeated, with identical procedure except the only water used was PR water, i.e., the 181 cc rain water dosing was replaced with a 181 cc PR water dosing. Finally, the experiment was repeated a third time, in which case the only water used was rain water, i.e., all dosing with PR water was replaced with dosing with rain water.

Hydraulic conductivity decreased significantly and substantially under conditions of repeated dosing with rain water to soils from three of the seven sampling sites. These three sites were also those which were ranked as having high risk of dispersion, based on soil chemical and physical conditions. It should be noted, however, that **these same soils demonstrated substantial reductions in hydraulic conductivity under all wetting circumstances, i.e., when all dosing water was low EC x low SAR and when rain water was introduced in the middle of the dosing sequence with water having low EC x low SAR.** The results of this experiment substantiated the conclusion that **dispersion is likely to occur in some of the subject soils upon wetting, irrespective of water quality. It appeared as though rain water did exacerbate reductions in hydraulic conductivity upon wetting.** However, dispersion and reduction in hydraulic conductivity did not appear to be a consequence or outcome of quality of simulated irrigation water applied to the subject soils.

A final laboratory assessment consisted of repeatedly dosing with rain water a soil column consisting of silty clay-silty clay loam having a relatively low exchangeable sodium percentage (average = 5.3% depth weighted). As in the previously reported laboratory studies, hydraulic conductivity was measured continuously during a series of wetting events. With the exception of an initial reduction in hydraulic conductivity after the first dosing event, there appeared to be no significant and consistent reduction in hydraulic conductivity in this soil, when subjected to repeated wetting with 'true' rain water.

Collectively, the results of these controlled laboratory experiments support the conclusions that: 1) dispersion and significant reductions in hydraulic conductivity likely occurred at various locations in the subject field as a result of a several-day period of rainfall; 2) dispersion was not necessarily a direct consequence of the quality of the rain water but rather a consequence of 'wetting'; 3) dispersion was specific to areas of the subject field characterized by soil having relatively high cation exchange capacity, more than 30% smectite clay, and relatively high exchangeable sodium percentage.

Inventory and assessment of irrigable, soils along a portion of the Tongue River near and below the T & Y irrigation district diversion revealed potential for substantial acreage of smectite-dominated clay soils, based on USDA-NRCS soil classifications available at http://websoilsurvey.nrcs.usda.gov/app/. Approximately 34% of the 6,315 acres of interest along the Tongue River corridor below the confluence with Circle L Creek consist of soil mapping units either having greater than 28% clay or are inclusive of soil mapping determined from Web Soil Survey to be within the field where crop loss and death was reported in 2006.

Ample evidence of rainfall-induced dispersion of clay and/or silt-dominated soils in circumstances of combinations of relatively low electrolyte concentration (salinity) and sodium, as expressed by either SAR or ESP, was found through a review of peer-reviewed, scientific journal literature. The following summarizes the significant evidences reported in the science literature. Elevated sodicity of soil solution or irrigation water can result in a significant decrease in soil hydraulic conductivity, while elevated soil solution or irrigation water salinity can mitigate (offset) the adverse effect of elevated sodicity on soil hydraulic conductivity, i.e., elevated salinity promotes fine particle flocculation. Structure of sodic soil can be maintained if salinity level is maintained above minimum threshold level. Flocculated, sodic soil will slake and disperse and soil structure will deteriorate if the salinity is decreased to a concentration below the minimum threshold level. Addition of rain water to a flocculated, sodic soil, can result in sufficient decrease in salinity to result in fine particle dispersion and deterioration of soil structure, particularly in the circumstance of 2:1 expansive clay-dominated, mineral soils (smectite), with low rates of mineralization or weathering. Probability of dispersion increases under conditions of intermittent rainfall. Soil dispersion has been documented under conditions of exchangeable sodium percentage as low as 1-2, and given conditions of salinity as low as 3.0 meq/liter (~ 0.3 dS/m), decreases in hydraulic conductivity and increases in clay dispersion occurred if the exchangeable sodium percentage exceeded 12.

Considering the findings of the undertakings of this study, the standards for salinity and sodicity, adopted by the Montana Board of Environmental Review for waters of the Tongue River,Powder River and other irrigation water sources of the Powder River Basin, appear to be both justifiable and protective, relative to sustainable use of Tongue and Powder River water for irrigation. This conclusion is based on past and current water quality conditions and water use practices, evidence of the presence of smectite-dominated clay soils within the irrigated margins of the Tongue River, results of chemical and physical analysis of soil materials collected, outcomes of controlled hydraulic conductivity measurements under intermittent dosing with representative water and rain water, and documentation appearing in peer-reviewed scientific literature.

Explanation of abbreviations and units of measure

EC – electrical conductance or specific conductance; reported as dS/m or mmhos/cm; mmhos/cm x 1000 = *u*mhos/cm. EC is used as a surrogate expression of salinity. For all practical purposes, EC can be related to salinity by the following: TDS (total dissolved solids) in mg/l = EC (in mmhos/cm or dS/m) x 640. This multiplier varies between approximately 640 and 680, depending on constitutent proportions.

SAR = sodium adsorption ratio (unitless in the context used here). SAR is determined as a ratio (with mathematical adjustment) of the concentration of sodium to the combined concentrations of calcium and magnesium SAR is a measure applied to solution – either soil saturated paste extract, soil solution, or irrigation water.

ESP = exchangeable sodium percentage (%). The ESP is an expression of the percentage of the soil cation exchange complex (or capacity) occupied by sodium.

montmorillonite = smectite-dominated clay size fraction

meq/l = milliequivalent per lilter; equivalent to mmolc/l). meq/l / 10 = EC (dS/m or mmhos/cm) for $0.1 < EC < 5$ dS/m

Introduction/Setting

Adverse effects of irrigation water salinity and sodicity on crop performance and soil physio-chemical conditions under some conditions are well-documented and have repeatedly been reported in internationally peer-reviewed science journals. In late September, 2006, an irrigated alfalfa producer in Custer county, Montana (MT) reported an incident of substantial alfalfa yield reduction and what appeared to be stand loss due to plant death, following a sequence of events involving irrigation, rainfall, and warm weather which contributed to high evapotranspiration demand. At the time of the incident, the alfalfa producer expressed concern about the potential of an adverse relationship between discharges of water associated with the extraction of coalbed natural gas/methane (CBNG/CBM) into the watershed from which irrigation water was sourced and quality of water being diverted for irrigation. Irrigation water applied to the field in question was sourced from the Tongue River (USGS cataloging units 10090101 and 10090102) via the

Tongue and Yellowstone (T&Y) irrigation district, headquartered in Miles City, MT. CBNG/CBM production water sourced in the Tongue River watershed of the Powder River Basin is known to have a diverse range in salinity and sodicity. Correspondingly, the alfalfa producer expressed concern that the apparent alfalfa yield loss and observed plant death was associated with salinity and sodicity sourced from irrigation water applied to the subject field.

Following the observed plant death, the alfalfa producer undertook deliberate efforts to investigate and document the circumstances, including securing a collection of aerial and ground photographs. For reference, the (generalized) location of the subject field is identified in Figure 1. The exact location of the subject field, including geographic coordinates, is identified in Figure 2. Figures 3 through 9, provided by the alfalfa producer, present visual evidences of the yield reductions and plant death, as recorded on October 8, 2006.

In assessing the circumstances coincident to the yield loss and plant death, the producer noted that the field had been planted to alfalfa June 15th, 2006. Additionally, the field had been irrigated in June and again on August 16th, 2006, with water sourced from the Tongue River, via T&Y irrigation district. The producer reported that subsequent to the August irrigation, the 'weather cooled somewhat and … some showers, then it warmed up until the 16th of September when the rain started, and over the next two weeks there was about 2.5 inches of rain and much cooler weather." According to National Weather Service records for Miles City, the area received intermittent rain for approximately 9 days (September 15-23), totaling > 1.6 inches of precipitation. The producer then hypothesized that the soil in the subject field had 'dispersed', consequent to sodium and/or salinity introduction from irrigation water, followed by dosing with low electrolyte (salt-free) rain water. Such a phenomenon is known to occur in sodium (Na)-dominated smectitic soils, has been reported in peer-reviewed science literature, and is referred to as 'rainfall-induced soil dispersion.

The irrigator subsequently contacted USDA-Natural Resources Conservation Service (NRCS) soil scientist (Steve Van Fossen) in Miles City. Mr. Van Fossen then completed an assessment, including review of historic and time-relevant aerial photographs, and collection and analysis of soil samples throughout the subject field and adjacent areas. Mr. Van Fossen collected ten GPS-located soil samples on November 28, 2006. The samples were subsequently analyzed for saturated paste extract pH, sodium, calcium, magnesium concentrations, and electrical conductivity. The cation concentration data was used to calculate sodium adsorption ratio (SARe). In a brief narrative, Mr. Van Fossen reported that the stand loss was most likely a consequence of inherent soil salinity and poor/inadequate drainage, likely a consequence of inherent soil conditions, land leveling, and irrigation water management combined with an extended period of rainfall, followed by high evaporative demand. (Personal communication via email Steve.VanFossen@mt.usda.gov, 12/6/2006. Copy of report included in appendix.) At the request of the irrigator, this researcher reviewed the data secured from Mr. Van Fossen and subsequently prepared a summary assessment. A copy of the report is included in appendix.

Figure 1. Approximate location of subject field.

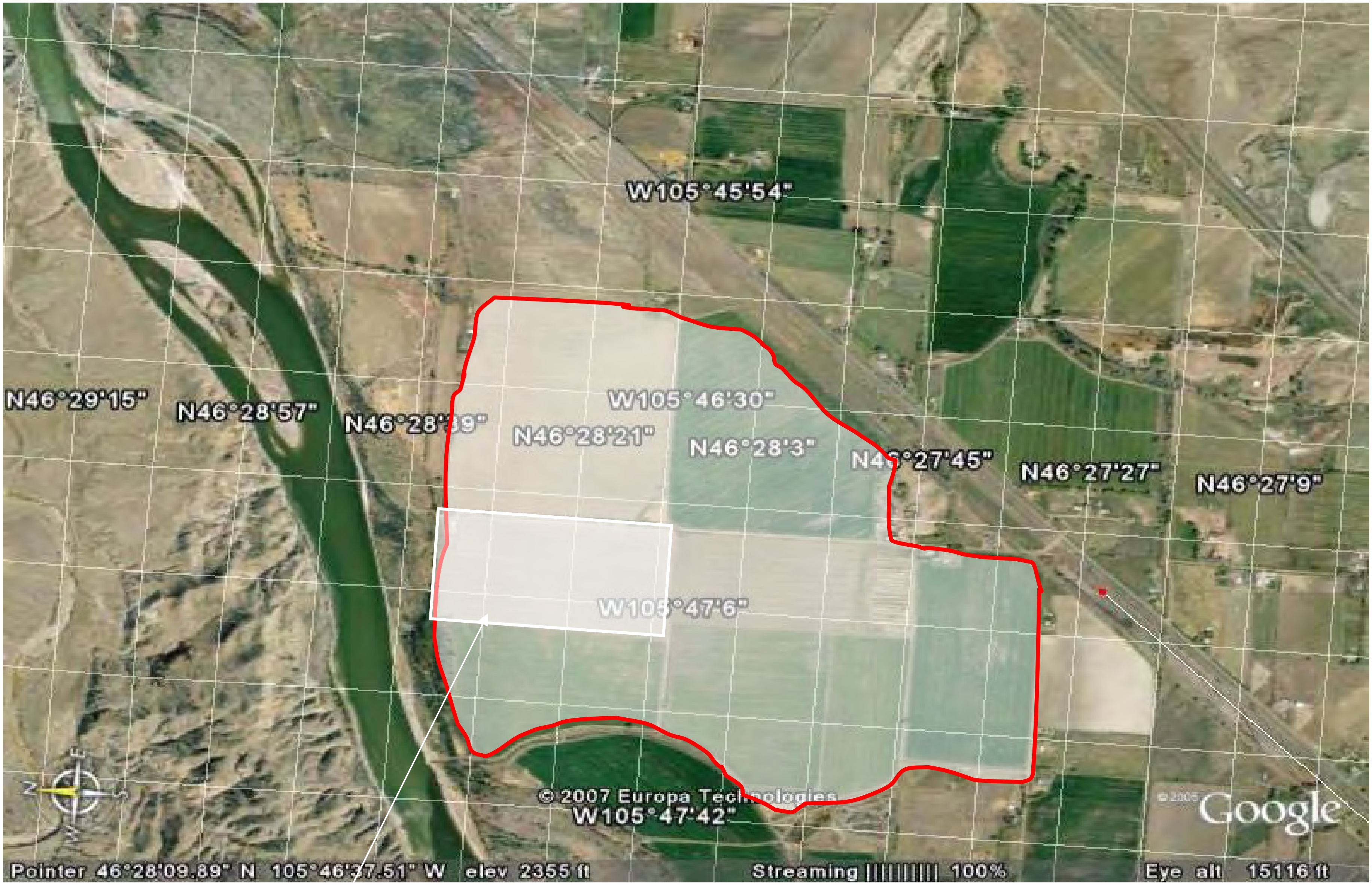


Figure 2. Subject field location. Source: Google Earth; 2006 image, prior to planting subject field.

Figure3. Direct overhead view of subject field. October 8, 2006. Photo courtesy of Roger Muggli, Miles City, MT.

Figure 4. Oblique view of subject field from perspective of viewing from southly to northerly direction. Note: Yellowstone River in background. October 8, 2006. Photo courtesy of Roger Muggli, Miles City, MT.

Figure 5. Low elevation oblique view of subject field from perspective of viewing from southly to northerly direction. Note: Yellowstone River in background. Lighter color areas constitute areas of yield loss and plant death. October 8, 2006. Photo courtesy of Roger Muggli, Miles City, MT.

Figure 6-9. Ground level views of alfalfa plants, October 15, 2006. Lighter color areas and bare ground constitute areas of yield loss and plant death. October 8, 2006. Photo courtesy of Roger Muggli, Miles City, MT.

Data reported by Van Fossen were reviewed on December 13, 2006 and the following response was presented in personal communication to Mr. Van Fossen. (Personal communication via email, jbauder@montana.edu to Steve.VanFossen@mt.usda.gov, 12/12/2006.)

- ECe of sites identified as M9 and M10 (*identified on VanFossen correspondence as representative of the subject areas where plant death and crop loss were noted*) were elevated above the average of the control sites (*those being sites identified on VanFossen correspondence as sites 3 and 5*). All of the subject field ECe values were greater than ECe values of the control sites, probably a reflection of evapoconcentration of salts at the soil surface. It was concluded that infiltration was restricted and ponded water on the soil surface of the subject site resulted in elevated EC when the ponded water evaporated.

- Elevated pH of site M10 was probably a consequence of elevated biological activity associated with green algae growth reported by VanFossen. The soil surface at site M10 most likely was near saturation and algae absorb carbon dioxide from the water and use the sun's energy to convert it to simple organic carbon compounds. As carbon dioxide in solution is removed, the soil water becomes more alkaline.

- Sodium concentration appeared to be much higher in the surface soils of sites M9 and M10 than in the surface soils from the control sites. (*According to the irrigator, as reported during a field site visit in June 2007, site M3 was irrigated at the same time as sites M10 and M9. ECe and sodium concentration of soil samples from site M3 were also elevated, although not to the level observed in samples from sites M10 and M9.*) This researcher reported that the elevated Na concentrations in samples from sites M10 and M9 could likely be a result of evapoconcentration at the soil surface, since sodium will move up with and remain at the wetting/drying front. Thus, as the soil at site M10 dried out, upward water movement brought sodium with it. An elevated sodium concentration of 206 meq l^{-1} was reported by Van Fossen for the surface soil sample of site M10.

- Calcium and magnesium concentrations of samples from site M10 increased as well… both … above the average of the control sites. This researcher concluded that the source water at the subject site had elevated total dissolved solids. Correspondingly, this elevated calcium and magnesium corresponded with an elevated concentration in total dissolved solids. “The cause for the elevated TDS – water sourced from either late-season return flows or seepage (upwelling) from areas adjacent to the canals… it could be possible the salinity was sourced from below as upward flow as water tables changed… it seems quite reasonable that the soil did disperse as a consequence of a leaching event and a reduction in soil solution salinity, caused by rainfall after the wetting event – especially given that the surface SAR in M10 0-0.25” sampling depth is 29.”

Circumstances of Study

The circumstances of the plant death and crop yield loss, apparently associated with irrigation with water sourced from the Tongue River, resulted in numerous questions and speculations regarding three issues of importance to agricultural crop irrigators in southeastern Montana:

1) the reality and susceptibility of rainfall-induced dispersion of selected soils subject to irrigation with water sourced from the Tongue and/or Powder River;

2) an explanation of the conditions and occurrences contributory to the crop yield loss and plant death reported in September, 2006; and

3) the protectiveness of in-stream standards of salinity (reflected in EC) and sodicity (reflected in SAR) established by the Montana Board of Environmental Review for the Tongue and Powder Rivers, Rosebud Creek, and associated tributaries.

Montana State University, Department of Land Resources and Environmental Sciences Extension water quality specialist subsequently submitted a proposal to Montana Department of Environmental Quality to conduct an independent assessment of the circumstances reported in 2006. Subsequently, studies were initiated to review quality of water of the Tongue River; complete soil sampling and analyses from locations within the subject field; conduct laboratory infiltration studies to assess the susceptibility of the subject soil materials to rainfall-induced dispersion; inventory irrigable, smectite-dominated clay soils along the Tongue River in Montana; complete a review of pertinent scientific literature; and evaluate the appropriateness and protectiveness of the Montana BER-adopted standards for salinity and sodicity of waters of the Tongue River.

Circumstances and quality of water of the Tongue River prior to the reported loss

The U.S. Geological Survey maintains a real-time accessible Tongue River Surface-Water-Quality Monitoring Network (http://tonguerivermonitoring.cr.usgs.gov/), which contains archived water quality data collected at various locations along the Tongue River, including a monitoring station identified as USGS 06307990 Tongue R above T & Y Div Dam near Miles City, MT. Pertinent data was retrieved for the period from May 1 through September 30, 2006, including mean daily discharge (cubic feet per second), maximum-minimum-mean specific conductance (uS/cm; comparable to umhos/cm), and predicted SAR. Additionally, grab sample analysis data for specific conductance and sodium adsorption ratio for the period from November 1, 2004 through November 16, 2007 were regressed (by U.S.G.S.) to obtain a prediction model allowing for estimation of SAR from specific conductance measurements. Summaries of data are presented in the appendix.

As a means of assessing potential risk of dispersion due to EC x SAR combinations of irrigation water sourced from the Tongue River, all U.S.G.S. grab sample EC and SAR data collected at the T & Y diversion station in 2206 were plotted on the dispersion risk figure reported by Hanson et al. (1999) (Figure 10). This figure, developed from data initially published by Oster and Schroer (1979) and subsequently modified by Ayers and Westcot (1994), presents the risk of dispersion of fine-textured soils subjected to various combinations of salinity and sodicity of irrigation water.

As can be seen from inspection of Figure 10, all but two samples collected from the Tongue River at T & Y diversion in 2006 had EC x SAR combinations which would be considered representing little or no risk of reduction in infiltration due to dispersion.

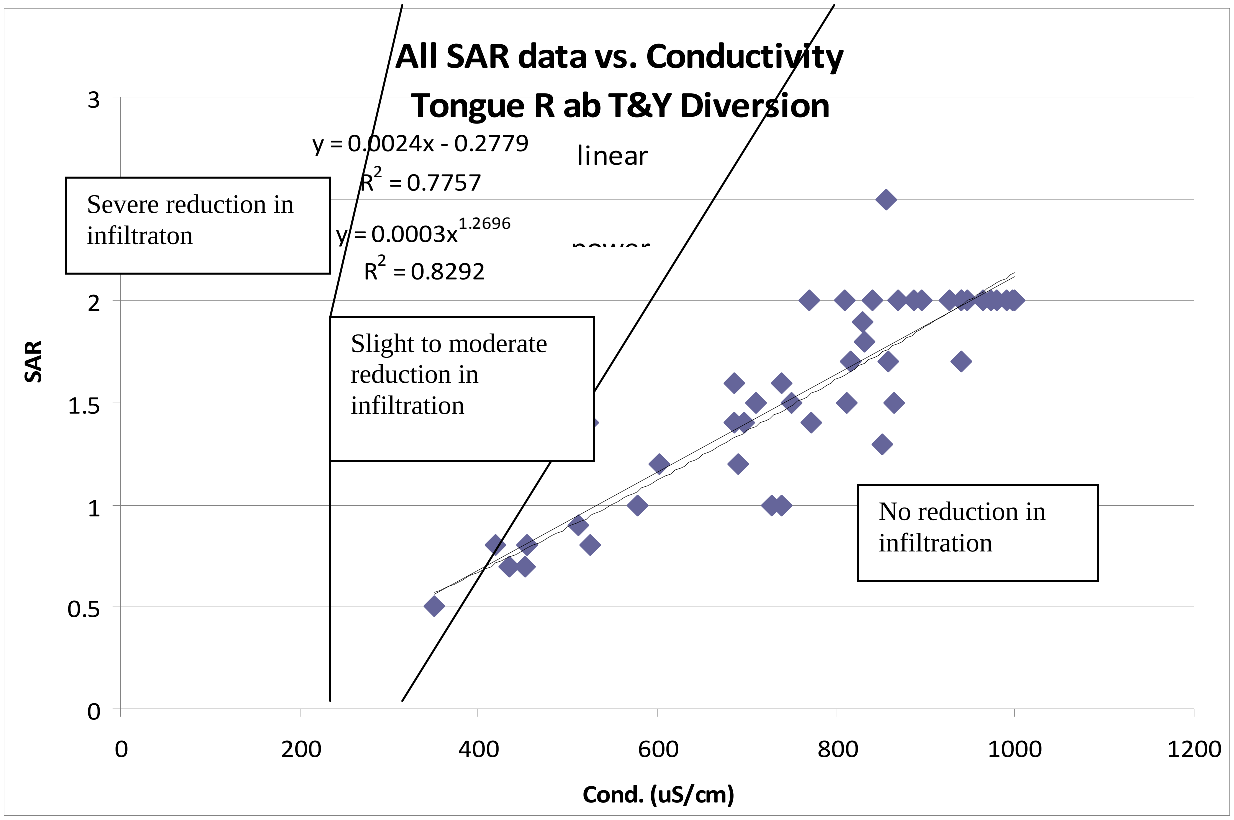


Figure 10. Electrical conductance (EC) v. SAR, Tongue River @ T& Y Diversion, 2006 water record. Source: USGS; http://waterdata.usgs.gov/nwis/uv?site_no=06307990. Lines inserted represent dispersion potential thresholds identified by Ayers and Westcot and Oster and Shroder (1979).

With regard to the Tongue River water chemistry data reported by the U.S.G.S. for 2006, statistics of importance are those preceding August 16th, the reported date of irrigation. Although the exact time period from diversion to point of delivery is not known, this is somewhat irrelevant, considering the water quality data obtained from the U.S.G.S. site.

Specific conductance of Tongue River water above the T&Y diversion (in August preceding August 16th) ranged from 652 *u*S/cm (equal to 0.65 mmhos/cm) on August 16th to a maximum of 730 *u*S/cm on August 2nd. Specific conductance averaged 707 *u*S/cm during the first 16 days of August, 2006. Hanson et al. (1999) report that typically soil saturated paste extract specific conductance of irrigated soils will equilibrate at a value approximating 1.5 to 3 times the specific conductance of the applied water, assuming adequate drainage to insure leaching and downward salt migration. In unrelated studies using soils obtained from along the Yellowstone and Powder Rivers, Bauder et al. (2008) reported similar findings, particularly in the case of fine-textured soils. Applying these approximations to Tongue River water, diverted via the T&Y irrigation diversion and applied to the subject field, it is reasonable to assume that equilibrium soil solution saturated paste extract specific conductance at the time of measurement by VanFossen would have been not more than 2,100 *u*S/cm (2.1 mmhos/cm), under circumstances of good drainage. In actuality, it is reasonable to assume that surface soil specific conductance would have been somewhat less than 2,100 *u*S/cm under conditions of good drainage, considering that several days of rainfall, totaling in excess of 1.5 inches, was reported after the irrigation event. (The national weather service reported precipitation 10 days between September 15 and 27, with 1.6 inches precipitation between September 15 and 23. See appendix.) This is further supported by the specific conductance values reported by VanFossen, in that all ECe values were less than 1.5 uS/cm (VanFossen reported dS/m, an equivalent value), except at site M10, where values of ECe = 26.3 and 4.4 dS/m (2,630 and 440 *u*S/cm, respectively) were measured.

Sodium adsorption ratio of Tongue River water above the T&Y diversion (in August preceding August 16th) ranged from 1.26 on August 16th to a maximum of 1.45 on August 3rd. Sodium adsorption ratio averaged 1.41 during the first 16 days of August, 2006. These values are consistent with SAR values reported by VanFossen, which averaged 1.7, with the exception of samples collected from sites M10 and M9. Bauder et al. (2008) reported previously that saturated paste extract SAR generally equilibrates at a level reasonably comparable to the SAR of applied water, under circumstances of adequate drainage.

In summary, **review of 2006 Tongue River water quality data at the T&Y diversion point, available from a U.S.G.S. automated gauging station, provided no overwhelming, convincing, or substantiating evidence of either elevated salinity or sodicity of irrigation water immediately preceding the reported August 16th, 2006 irrigation event.** Ancillaray to assessment of Tongue River water quality at the T & Y diversion, comparison of specific conductance and SAR of Tongue River water at T & Y diversion with specific conductance and SAR of Tongue River water at Brandenberg Bridge in 2006 revealed that specific conductance increased approximately 18% between Brandenberg Bridge and T & Y diversion during the first 16 days of August 2006. Correspondingly, SAR increased approximately 11% during the same period.

With exception of data from sites identified as M9 and M10, soil saturated paste extract data collected shortly after the September 2006 event and reported by Van Fossen were found to be consistent with expectations, considering the U.S.G.S. reported Tongue River water quality. Other than the exceptions noted, soil saturated paste extract averaged 871 *u*S/cm, only 23% greater than the specific conductance of Tongue River water at the T & Y diversion at the time of the August 16th irrigation, while soil saturated paste extract SAR averaged 1.68, only 22% greater than the SAR of Tongue River water at the T & Y diversion at the time of the August 16th irrigation.

Follow-up soil assessment: soil sampling, physical and chemical analyses from locations within and in proximity of the subject field

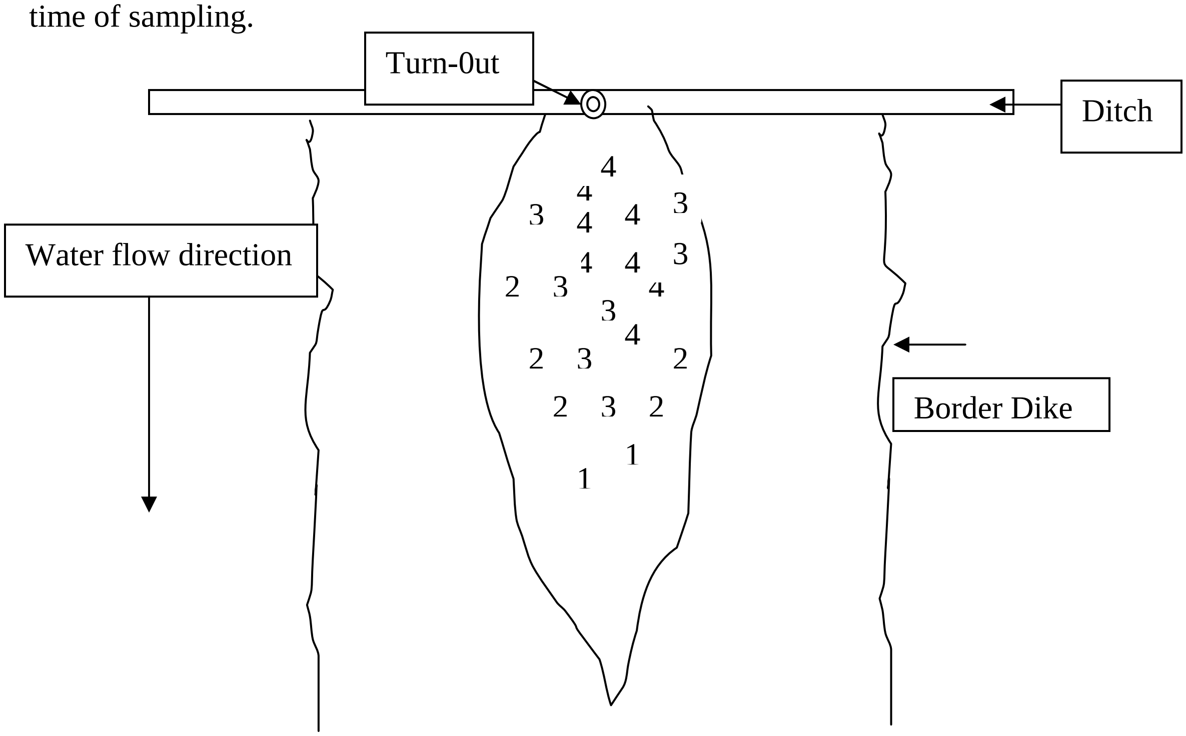
Field site inspection and soil sampling was completed on July 20, 2007. In advance of field sampling, the report prepared by Steve VanFossen was reviewed and tentative sampling sites were located. Additionally, soil survey data for the subject site was accessed via the U.S.D.A.

NRCS Web Soil Survey 2.0, National Cooperative Soil Survey. Figure 11 constitutes a representation of soil mapping units at and in the vicinity of the subject field. The U.S.D.A. National Cooperative Soil Survey characterizes essentially all of the subject field and significant portions of adjacent fields as mapping unit 53A, Kobase silty clay loam. Within the boundaries of the area of interest (outlined in blue), Kobase silty clay loam accounts for 58.8% of the area while Yamacall loam accounts for the balance of 33.5%.

Nine sampling sites were initially identified from soil survey images. Following discussion with the irrigator and subsequent field inspect, 7 sites were selected for sampling. The approximate locations of the sampling sites are indicated on Figure 11. Approximate sampling locations with respect to aerial images of the subject field at the time of damage are identified in Figure 12.

Upon arrival at the designated sampling site, each sampling location was GPS located and recorded. Specific locations are included in the appendix. Additionally, photographs of crop canopy and soil surface condition were collected. Soil samples were collected and separately bagged from the 0-5, 5-10, 10-15, and 15-30 cm depth increment (0-2”, 2-4”, 4-6”, 6-12”). A composite sample was collected at each site, as follows: 4 corner locations of a 4 m x 4m grid were sampled, respective depth increments placed in separate mixing buckets. The composited material was thoroughly mixed, after which a 2.5 kg sample was transferred to a soil sample bag. Each bag was appropriately labeled and placed in a cooler. Samples were subsequently transported to Montana State University-Bozeman for processing and analysis.

An observation made during field site inspection and soil sampling was that it appeared as though most of the significant plant death was associated with infiltration (or lack thereof) and duration of standing water associated with irrigation ditch turn-outs and proximity to clay-dominated soil. The following provides a graphic representation of observation made during sampling. In the illustration, the magnitude of crop loss and plant death is characterized by a number, ranging from 1 to 4, with 4 representing the greatest degree of plant death evident at the time of sampling.



Numerous photographs, illustrating the condition of the alfalfa crop and soil surface conditions, were collected at the time of soil sampling. Selected images are presented as follows in Figures 14-17.

Soil Sample Analyses

Upon return of soil samples to Montana State University-Bozeman, all soil samples were dried at 95 °C, then ground and sieved through a 10-mm sieve to prepare for particle size analysis (PSA) and powder X-Ray diffraction (XRD). A 10-mm sieve screen was used with the intent of preserving aggregates up to a diameter of 10-mm in size. A subsample of the sieved material was subsequently fine-ground to pass through a 2-mm sieve. Soil passing through the 2-mm sieve was used for particle size analyses (PSA), chemical analyses, and powder X-ray diffraction (XRD) analyses. Soil passing through the 10-mm sieve was used for infiltration assessments of rainfall-induced dispersion.

The hydrometer method of PSA was completed according to protocol outlined in Methods of Soil Analysis Part 1, Black et al, 1965, pp.562. Assuming that infiltration was likely most influenced by soil physical properties at the soil surface, PSA was completed only for soil material from the 0-5 and 5-10 cm depth increments (0-2”, 2-4”). Results of PSA are presented in Table 1.

Table 1. Percent sand (> 50*u*, i.e., 2-0.05mm), silt (2-50*u*), clay (< 2*u*), and soil textural class of soil samples from 0-2” and 2-4” depth of selected sites within and in vicinity of subject field. Sample ID numbers for laboratory use only; site identification numbers correspond to locations identified in Figures 11 and 12.

Sample ID	site	Depth (inches)	% sand[1/]	% silt	% clay	soil texture[2/]
1	1	0-2	7.4	32.6	60	clay
2	1	2-4	5	33	62	clay
3	2	0-2	37.3	34.7	28	clay loam
4	2	2-4	40	32	28	clay loam
5	3	0-2	25	41	34	clay loam
6	3	2-4	22	42	36	clay loam
7	4	0-2	18	44	38	silty clay loam
8	4	2-4	14	44	42	silty clay
9	5	0-2	22.4	41.6	36	clay loam
10	5	2-4	24	38	38	clay loam
11	7	0-2	19	37	44	clay
12	7	2-4	16	36	48	clay
13	9	0-2	32	36	32	clay loam
14	9	2-4	36	35	29	clay loam

[1/] % determined as (grams dry weight of separate per gram dry weight of soil) x 100%.
[2/] soil texture determined from soil textural triangle (source: http://www.pedosphere.com/resources/bulkdensity/)

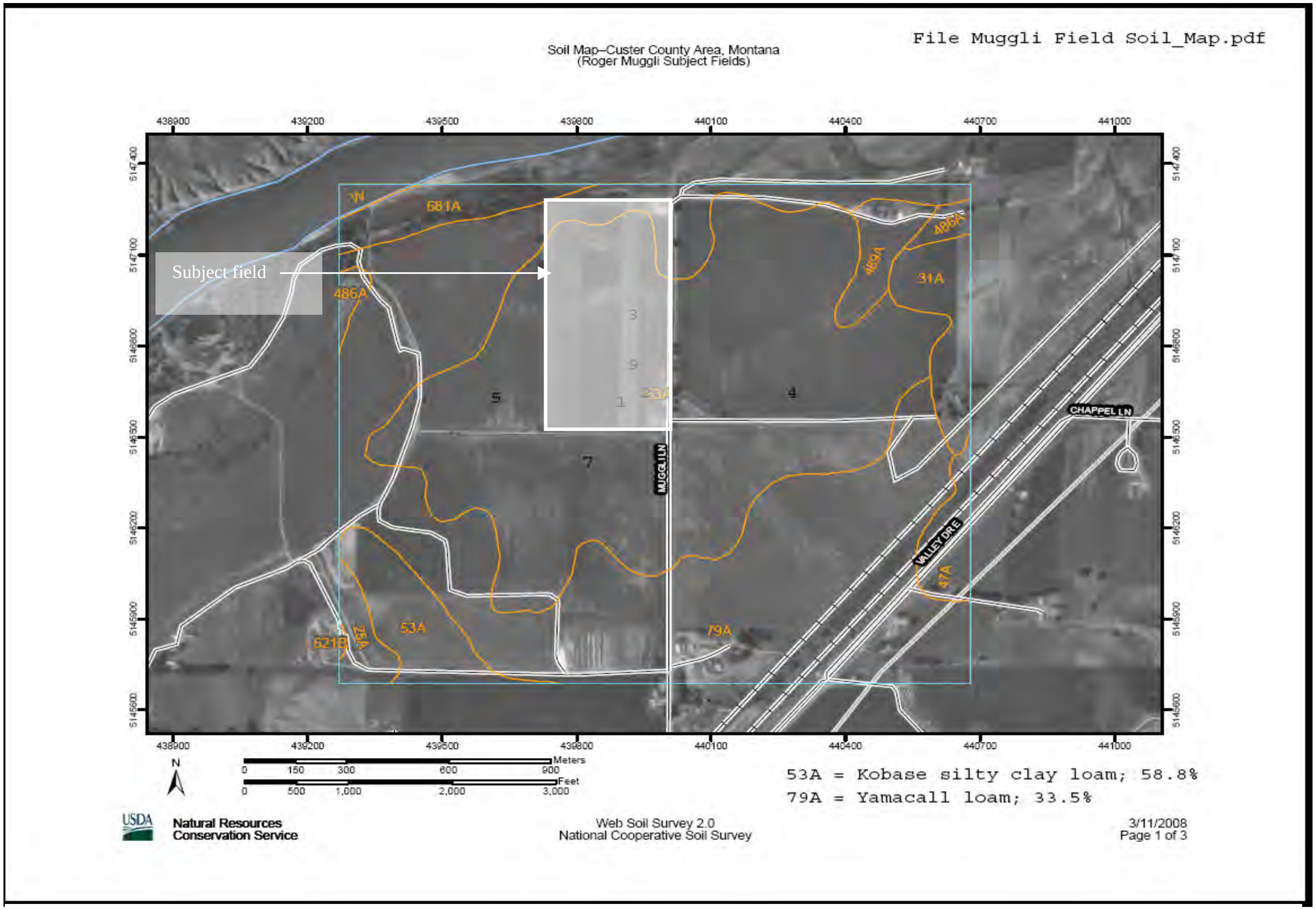
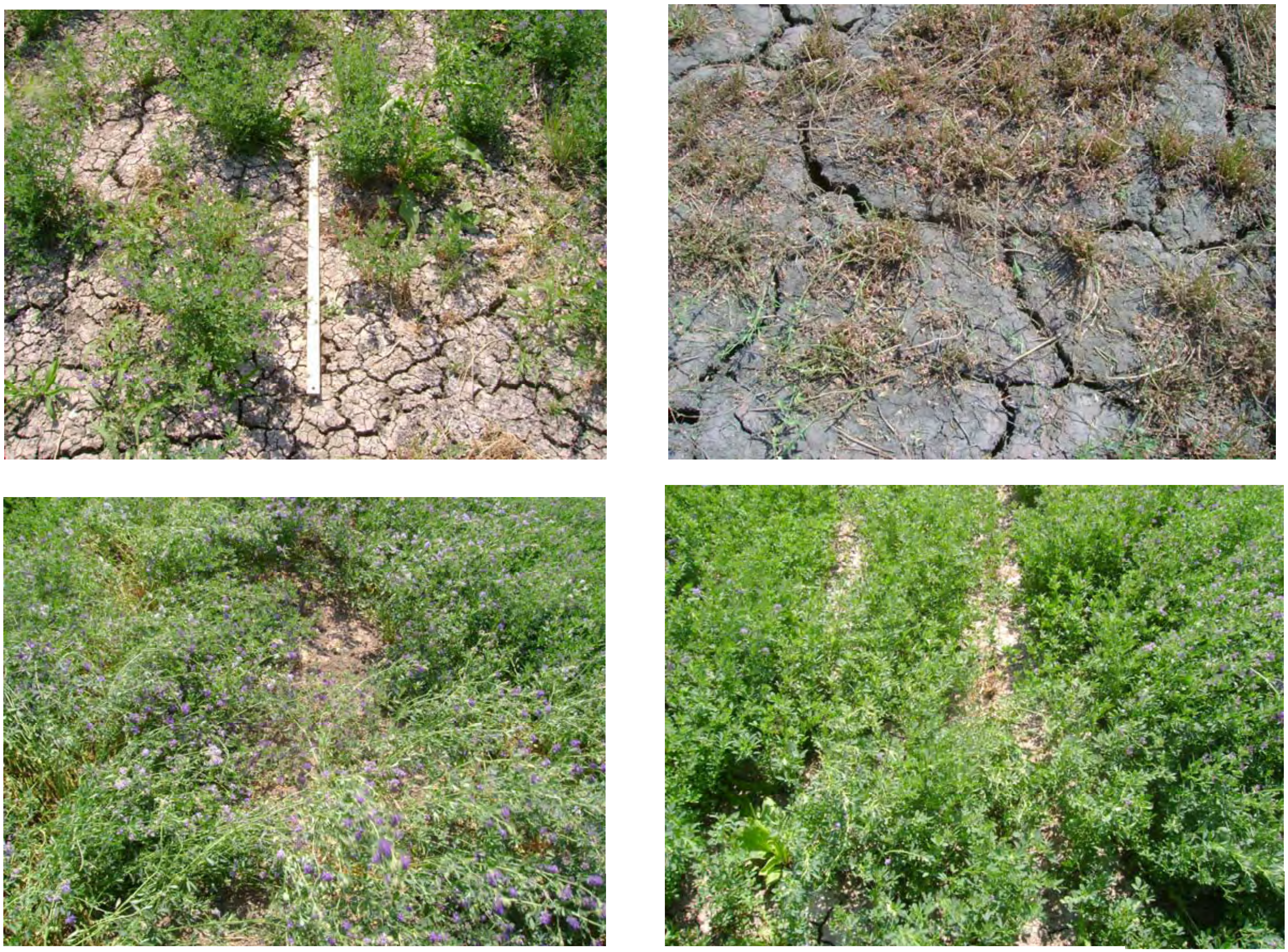


Figure 11. Soil mapping unit delineations at and in vicinity of subject field. Number x letter combinations represent soil mapping units. Individual numbers identified approximate sampling point locations. Source: U.S.D.A. NRCS Web Soil Survey 2.0, National Cooperative Soil Survey. Accessible at (http://websoilsurvey.nrcs.usda.gov/app/).

Figure 12. Approximate location of soil sampling points. GPS location of sampling points included in appendix. Sampling points were selected on basis of evidence of crop death, reference to sampling points identified by Steve VanFossen, aerial images and soil mapping unit boundaries

Figure 13. Approximate perimeter of sampling area.



Figures 14-17. Selected images of soil surface and alfalfa crop condition at time of soil sampling, July 19, 2007.

As shown in Table 1, **all of the samples for which PSA was completed included of a significant clay fraction, ranging from 28 to 62% clay on a dry mass basis. Noteworthy were samples from sites 1, 4, 5, and 7, which all had clay fractions exceeding 35%. All samples classified as 'clay', 'clay loam', or 'silty clay loam'.**

XRD analysis was completed by the Image and Chemical Analysis Laboratory at Montana State University. XRD analysis was completed for samples from the 0-5 and 5-10 cm (0-2", 2-4") depths of all sample locations. Less-than 2*u* diameter subsamples were mounted in a side loader mount and analyzed on a Scintag Inc. XGEN-4000 with a Cu Kα source. Dried samples were run from 4 to 75 degrees 2θ at 0.05 degrees/minute with a step size of 0.5 degrees. Samples were then rewetted to test for the presence of smectite clays. Water was added to samples until they would not absorb any more water and a thin film of standing water remained. This procedure assured that clays would be fully solvated. Wet clay samples were run at a (higher) resolution of 0.02 degrees/minutes from 3 to 15 degrees with a step size of 0.02 degrees, to better resolve their peaks above background. Detailed results of the XRD analysis are included in the appendix.

The first run, dry sample XRD analysis, identified a 'peak' at 14 Å peak, and 7 Å in all of the samples analyzed. These peaks are indicative of presence of some combination of chlorite, smectite, or kaolinite. A few of the samples revealed a small 10 Å peak, just above background. The 10 Å peaks are indicative of micas or illite. The 10 Å peaks were barely above background. Chlorite has a 14Å and a 7Å peak, smectite clays have a peak at 14Å, and kaolinite has a peak at 7Å. It was not possible to distinguish between chlorite, smectite, and kaolinite based on these sample XRD patterns, which were derived from 'dried' samples.

The inability to distinguish chlorite from smectite from kaolinite in dry sample analysis necessitated hydrating the sample materials and completing a second XRD analysis of each sample. Correspondingly, as previously noted, each sample was wetted to completely solvate the clays present. Once wetted, XRD analyses were completed.

In all cases (samples 1-14), the 14 Å peaks shifted to ~20 Å's peak upon wetting, confirming the predominant clay component to be smectite clay. No peaks remained at 14 Å, indicating the absence of chlorite from all samples. **With respect to abundance, the clays present in the samples are: smectite >> kaolinite > mica/illite.**

Subsamples of all soil samples were submitted to AgSource Harris Laboratories, Lincoln, NE, (http://ag.agsource.com/) for complete chemical characterization. Each sample was analysed for determination of saturated paste electrical conductivity, extractable and exchangeable cations, and cation exchange capacity. Upon receipt of the results of analyses, the data were organized by parameter, site, and sampling depth increment. The pertinent results are summarized in Table 2.

Parameters of particular interest include: cation exchange capacity; electrical conductivity (specific conductance of saturated paste extract); sodium, calcium, and magnesium concentrations; sodium adsorption ratio; and exchangeable sodium percentage.

Table 2. Summary of results of chemical analyses of soil samples. Analyses completed by AgSource Harris Laboratories, Lincoln, NE. In addition to the soil samples collected from the seven sampling locations identified in Figures 11 and 12, a single, composite sample of 'bulk deposit' was collected by aggregating surface samples collected immediately downgradient of 5 irrigation turnouts in the subject field.

Cation Exchange Capacity (meq/100 g dry soil)								
Sample Depth (in)	Site 1	Site 2	Site 3	Site 4	Site 5	Site 7	Site 9	Bulk deposit
0-2	34	26.2	27.1	27.3	31.3	33.1	30.8	35.4
2-4	29.2	26.2	30.7	28.3	28	31.8	30.1	
4-6	38.6	26.6	32	31.3	33.7	33.6	28.5	
6-12	42.1	30.2	32.2	31.7	37.3	36.9	31.3	
Depth wtd*	38.0	28.3	31.1	30.3	34.2	34.9	30.6	
Electrical Conductivity (mmhos/cm) (saturated paste extract, ECe)								
Sample Depth (in)	Site 1	Site 2	Site 3	Site 4	Site 5	Site 7	Site 9	Bulk deposit
0-2	0.78	0.82	0.57	0.59	0.45	0.55	0.69	1.95
2-4	0.94	0.86	0.50	0.52	0.49	0.53	0.71	
4-6	1.25	0.97	0.48	0.39	0.77	0.60	1.09	
6-12	2.0	1.37	0.63	0.41	1.28	0.79	1.57	
Depth wtd*	1.5	1.1	0.6	0.5	0.9	0.7	1.2	
Sodium (ppm, saturated paste extract)								
Sample Depth (in)	Site 1	Site 2	Site 3	Site 4	Site 5	Site 7	Site 9	Bulk deposit
0-2	447	235	123	82	265	163	120	125
2-4	449	264	161	103	361	259	163	
4-6	800	332	192	118	736	436	175	
6-12	1417	490	250	130	1440	928	326	
Calcium (ppm, saturated paste extract)								
Sample Depth (in)	Site 1	Site 2	Site 3	Site 4	Site 5	Site 7	Site 9	Bulk deposit
0-2	4138	3430	3710	3698	4191	4484	4175	4546
2-4	3588	3445	4139	3871	3640	4291	4151	
4-6	4520	3412	4200	4329	4009	4324	3842	
6-12	4645	3574	4155	4560	3994	4516	3935	
Magnesium (ppm, saturated paste extract)								
Sample Depth (in)	Site 1	Site 2	Site 3	Site 4	Site 5	Site 7	Site 9	Bulk deposit
0-2	1292	934	918	957	1050	1114	1026	1365
2-4	1065	907	1071	982	951	1046	965	
4-6	1431	944	1171	1057	1214	1159	957	
6-12	1459	1192	1195	954	1281	1185	1163	

Sodium Adsorption Ratio (saturated paste extract)								
Sample Depth (in)	Site 1	Site 2	Site 3	Site 4	Site 5	Site 7	Site 9	Bulk deposit
0-2	1.55	0.91	0.47	0.31	0.94	0.56	0.43	0.42
2-4	1.68	1.03	0.57	0.38	1.37	0.92	0.59	
4-6	2.64	1.30	0.67	0.42	2.60	1.51	0.65	
6-12	4.63	1.81	0.88	0.46	5.06	3.17	1.17	
Depth wtd*	3.3	1.4	0.7	0.4	3.3	2.1	0.9	
Exchangeable Sodium Percentage (%, on dry soil basis)								
Sample Depth (in)	Site 1	Site 2	Site 3	Site 4	Site 5	Site 7	Site 9	Bulk deposit
0-2	13.82	16.79	8.12	5.51	8.95	7.25	6.82	8.19
2-4	20.89	18.70	6.51	5.30	13.57	9.43	8.64	
4-6	21.50	21.80	7.19	5.11	18.69	12.50	12.98	
6-12	33.73	28.15	11.49	5.36	27.88	18.16	21.41	
Depth wtd*	26.2	23.6	9.4	5.3	20.8	13.9	15.4	
Organic Matter (%, [(g OM/g dry soil) X 100%])								
Sample Depth (in)	Site 1	Site 2	Site 3	Site 4	Site 5	Site 7	Site 9	Bulk deposit
0-2	2.8	2.4	3.8	3.2	2.8	2.6	3.4	2.7
2-4	2.8	2.4	3	3	2.7	2.5	3.4	
4-6	2.5	2.1	2.8	2.8	2.5	2.5	3.2	
6-12	2.1	2.2	2.6	2.4	2.2	2.3	2.7	
Nitrate (NO_3, ppm, extractable)								
Sample Depth (in)	Site 1	Site 2	Site 3	Site 4	Site 5	Site 7	Site 9	Bulk deposit
0-2	24.2	36.5	29.5	36	11.1	33.9	27.4	205.8
2-4	19.7	33.6	24.2	32.8	11.5	22.7	21.0	
4-6	12.6	20.3	17.9	19.0	15.7	19.3	29.8	
6-12	5.6	15.8	15.4	14.6	11.0	14.0	21.0	
Phosphorus (ppm, extractable)								
Sample Depth (in)	Site 1	Site 2	Site 3	Site 4	Site 5	Site 7	Site 9	Bulk deposit
0-2	8	8	11	10	16	15	34	7
2-4	7	6	7	7	19	8	35	
4-6	6	1	1	1	9	6	38	
6-12	2	1	1	1	7	5	18	

Depth wtd*: Depth weighted, per inch average value, was calculated, for comparison purposes. Number represents average value per inch of soil, 0-12".

Cation exchange capacities of all samples were relatively consistent and generally reflective of exchange capacities reported in scientific literature for soil materials categorized as 'smectite clay-dominated' (http://www.clays.org.au/mins.htm). Noteworthy are the cation exchange capacities through the 12-inch sampling depth of sites 1, 5 and 7. These exchange capacities serve as good surrogate indices of relatively high clay content and most likely reflect abundance of smectite clays – consistent with XRD analyses results. In contrast, exchange capacities of samples from sites 2, 3, 4 and 9 are somewhat lower. As a means of offering a mechanism for comparison among sampling sites, a single, depth-weighted average value was calculated for each parameter at each sampling site. This was done by: 1) multiplying each parameter value by the associated depth increment, i.e., 2 or 6”; 2) accumulating each of these products for the four samples for the respective sampling site; and 3) dividing this accumulated total by 12, representing 12” sample depth. Noteworthy is the fact that sites 2, 3, 4, and 9 constitute areas of limited evidence of plant death and crop loss, as evidenced from aerial photographs taken October 8, 2006 (see Figure 12). Additionally, these sites had lesser depth-weighted cation exchange capacities than sites 1, 5 and 7.

The other parameters of relevance in this regard are the ECe, SAR and the ESP. All ECe values were relatively low, and non-reflective of a salinity hazard, based on published salinity thresholds. The ECe values were consistent with those reported by VanFossen, who reported highest ECe values for his sites referenced as M10 and M9, respectively. These sites would have corresponded reasonably closely with sites 1 and 5 of the present study. Site 1 of the present study had the highest depth-weighted ECe.

Sodium adsorption ratio ranged from < 0.3 (site 4, 0-2” depth) to 5.60 (site 5, 6-12” depth). As with CEC, maximum individual and depth-weighted SAR values were measured on samples from sites 1, 5 and 7. Depth-weighted SAR for these three sites were determined to be 4.63, 5.06, and 3.17. With respect to published thresholds for SAR, these values fall below the U.S.D.A. threshold of 12. On initial inspection, none of these SAR values would appear alarmingly high.

A word of caution and explanation needs to be considered when reviewing both the ECe and SAR values. These metrics were derived from chemical analyses of saturated paste extracts and reflect soluble salts in the soil at the time of sampling. The ECe reflects to some degree the inherent salinity and/or weathering characteristics of the soil material at the site. Especially elevated salinity (none evident in this case) would be clear reflections of poor or inadequate internal drainage and/or upward movement of water at the time of sampling. Correspondingly, in this case a measure of SAR from a saturated paste extract provides a only general index and such a value has the potential to be characteristic of transient conditions and/or those experienced at the time of sampling, and not necessarily at the time of crop death.

The most revealing soil chemical property statistic is the exchangeable sodium percentage (ESP), which is a resilient soil property, reflective of true soil chemistry. Values ranged from 5.11% in the 0-2” depth of site 4 to 33.73% in the 6-12” depth of site 1. In comparison to the historically accepted ESP threshold of 15% in swelling-clay dominated soils, 11 of the 28 samples had ESP values exceeding this threshold. Sites 1, 2, and 5 had depth-weighted ESP values exceeding 20%, with clearly an abundance of exchangeable sodium in the 4-6” and 6-12” depth samples.

As a means of identifying trends and/or common characteristics of impacted sites, the soil chemical and physical property data reviewed and ranked, according to risk of dispersion. Ranking was as follows – based on best professional judgment/assessment of risk of dispersion:

Clay percentage = reflection if swelling potential, risk increases with increasing clay %
CEC = reflection of smectite clay content, risk increases with increasing CEC
EC = reflection of solution salinity, risk increases with decreasing EC
Sodium = contributor to dispersion, risk increases with increasing concentration
Calcium = flocculating component, risk decreases with increasing concentration
Magnesium = dispersing agent, risk increases with increasing concentration
SAR = reflection of dispersion potential, risk increases with increasing SAR
ESP = reflection of dispersion potential, risk increases with increasing ESP
OMatter = aggregation component, risk decreases with increasing concentration

After the data was ranked, a score of 1-7 was assigned to each value, with 7 representing highest risk, based on best professional assessment. The scored values were then tabulated and a composite risk score was calculated for each site. Table 3 constitutes a summary of the rankings and the composite risk score for each site.

Table 3. Best professional judgement dispersion risk assessment, aggregated risk score, and resultant site ranking of risk of dispersion.

Site	CEC	EC	Na	Ca	Mg	Ca:Mg	SAR	ESP	Average Score	Rank – Risk of Disperson
1	6	2	7	5	7	5	7	6	5.6	7
2	1	3	5	7	1	4	5	7	4.1	4
3	3	6	3	3	2	3	3	2	3.1	3
4	2	5	1	6	4	3	1	1	2.9	2
5	4	7	6	4	5	3	6	5	5.0	6
7	7	6	4	1	6	2	4	4	4.3	5
9	5	4	2	2	3	1	2	3	2.8	1

Using this procedure, the greatest risk of dispersion appeared to be at site 1, followed by sites 5 and 7. Least risk of dispersion appeared to be at sites 9, 4, 3, and 2.

In summary, **soil chemical analyses confirmed that plant death and yield loss was not likely a result of excessively elevated salinity. Additionally, plant death, based on visual evidence, was coincident with locations in the subject field where soil was 'smectite-clay' dominated. Soil in the areas where the greatest extent of death and plant loss occurred had greatest depth-weighted cation exchange capacity, greatest depth-weighted SAR, and greatest depth-weighted ESP.** Although it was not possible to gather actual plant response/death data at the time of the reported incident, visual evidence in the form of aerial photographs confirms that maximum extent of crop loss and plant death most likely was consistent with this ranking.

The soil physical and chemical analyses data, when combined with evidences of plant death, provide reasonably substantial evidence that conditions of relatively low ECe, in combination with relatively low SAR values, can result in significant death of crops such as alfalfa. However, **it is likely**, as documented in a literature review, **that plant death was a consequence of an extended period of soil saturation, brought on by multiple days of rainfall, resulting in an oxygen deficiency in the soil.**

The ESP values, previously reported in the scientific literature as indicative of elevated potential of dispersion of smectite-dominated soils, were found to be consistent with the reported threshold of 15% ESP. In this particular case, however, the relationship between saturated paste extract SAR and ESP did not prove consistent with that reported in scientific literature. ESP was determined to be 10 or more times greater than SAR in most cases. It appears in this case the ESP is a better indicator of dispersion potential than the combination of ECe and SAR. **Assuming that soil dispersion was an operative factor of significance in the death of the alfalfa in the subject field, it appears that ESP is likely a better indicator of dispersion potential than is SAR.**

Laboratory infiltration studies of rainfall-induced dispersion following wetting with water having relatively low salinity and sodicity

As a means of assessing the likelihood of rainfall-induced dispersion of the soil material of the subject field, bulk soil material was collected from the 0-2”, 2-4”, 4-6”, and 6-12” depth of each of the previously described/defined sampling locations in July 2007. Each sample amounted to approximately 2 kg (5 pounds) of soil material. The material was obtained by compositing approximately 2 pounds of material from each of four locations within a 4m x 4m sector, thoroughly mixing the composited material, and then extracting a 5 pound subsample. The soil was placed in a soil sample bag, labeled and stored in a cooler. Upon return to Montana State University-Bozeman, each soil material was air dried at 70^{o}F for 96 hours. The dried soil was sieved through a 10 mm sieve, with the balance of material remaining on the sieve being hand ground to pass through the sieve. The soil was then archived until laboratory experimental procedure was defined and appropriate water sources could be secured.

An infiltration apparatus, consisting of a soil chamber, water droplet tower, water delivery mechanism and water supply reservoir was constructed. The entire infiltration apparatus was positioned within the center of the raindrop receptor screen of an ‘Onset’ model RG2/RG2-M data logging rain gauge (tipping bucket), equipped with a ‘BoxCar’ version 3.7+ ‘HOBO’ data logger. Manufacturer of the ‘Onset’ tipping bucket rain gauge reported accuracy of 0.01” inch equivalent rainfall depth, when operated with a 6” diameter, screened opening. For purposes of the infiltration studies, an infiltrating surface area of 3.25” diameter was used and appropriate modifications to conversion of HOBO-recorded data to rainfall/infiltration equivalent were completed.

The first set of laboratory experiments consisted of a protocol of nine (9) intermittent wetting/dosing events, with drip water application to the soil surface at near-saturated hydraulic conductivity rates, based on initial wetting of the soil. Intermittent dosing consisted of simulated irrigation water and rainfall. Approximately 1.5 cm depth of bulk soil from the 2-4” sampling depth was instantaneously placed within the bottom of the infiltration cylinder. An additional 1.5 cm depth of bulk soil from the 0-2” sampling depth was subsequently placed on top of the first soil increment. The apparatus was then gently agitated to facilitate mixing/blending between the two soil deposits. The apparatus was then placed within the receiving screen of the ‘Onset’ tipping bucket rain gauge.

A predetermined amount of water was then transferred to the supply reservoir and the water delivery hose was positioned over the center of the soil surface, approximately 20 cm above the soil surface. At a pre-determined time interval, a stop valve on the water delivery hose was opened, allowing water to transfer from the water supply reservoir to above the soil surface. Water was allowed to drip onto the soil surface at a rate comparable to approximately 0.06 cm equivalent depth/minute (3.6 cm/hr; ~ 1.4 inches/hour). Water passing through the soil in the infiltration cylinder was measured continuously until infiltration and subsequent drainage ceased. Volume of water passing through the soil and into the recording rain gauge was logged continuously with the 'BoxCar' HOBO data logger. Infiltration was subsequently calculated as Q (volume of water collected)/unit area/unit time.

As a means of avoiding complications associated with synthesis of water to be representative of 'true' in-stream conditions and to use water representative of circumstances associated with water quality standards established by the Montana Board of Environmental Review for in-stream salinity and sodicity, water used in the initial infiltration studies was obtained directly from the Powder River, immediately downstream of the U.S.G.S. real time gauging station at Moorhead, MT (USGS 06324500 Powder River at Moorhead MT). This station reports in-stream specific conductance and SAR (calculated) (http://waterdata.usgs.gov/nwis/uv?06324500). Specific conductance of simulated irrigation water used in these assessments was 1.38 dS/m (1.38 mmhos/cm @ 25^{o}C) and SAR was ~3.05.

Rainwater was collected in bulk directly from the downspout of a rain collection system located at a private facility at Moorhead, MT at approximately the same time bulk river water was collected. Rain water had a measurable specific conductance of < 0.05 dS/m (0.05 mmhos/cm @ 25^{o}C) and SAR was non-detectable. For ease of explanation, simulated irrigation water is denoted as **PR water** and rainwater is designated as **rainwater.** An equivalent depth of 3.25 cm (1.28 inches) of rainwater was applied over a sequence of four events. This was interspersed with an equivalent depth of 17.5 cm (6.9 inches) of irrigation water.

Dosing consisted of the following sequence and interval of events, using configurations of 0-2" and 2-4" soil from all seven sampling locations previously described. The intent of this protocol was to evaluate rainfall-induced dispersion.

1. At the start of recording of the collection bucket (a tipping bucket rain gauge, equipped with HOBO data logger), transfer **274 cc of PR water** (equivalent to 5.0 cm depth irrigation water) to the transfer tank and initiate drip wetting. (Approximately 6 minutes to apply this amount of water to the surface of the infiltration basket.)
2. Allow infiltration to proceed until completion with extended total time between initiation of wetting and initiation of next step (#6) being **20 minutes** (start to finish).
3. Transfer **27 cc of rainwater** (equivalent to 0.25 cm depth of rainfall) to the transfer tank and initiate drip wetting.
4. Allow infiltration to proceed until completion with extended total time between initiation of step #6 and initiation of next step (#8) being **10 minutes** (start to finish).
5. Repeat steps 6 and 7. **27 cc of rainwater**
6. Repeat steps 6 and 7. **27 cc of rainwater**
7. Allow equilibration time of 1 hour

8. Transfer **137 cc of rain water** (equivalent to 2.5 cm depth rainfall) to the transfer tank and initiate drip wetting. Approximately 12 minutes to apply this amount of water to the surface of the infiltration basket.
9. Allow equilibration time of 2 hours
10. Transfer **137 cc of PR water** (equivalent to 2.5 cm depth irrigation) to the transfer tank and initiate drip wetting. Approximately 6 minutes to apply this amount of water to the surface of the infiltration basket.
11. Allow infiltration to proceed until completion with extended total time between initiation of wetting and completion of this step being 60 minutes (start to finish).
12. Transfer **137 cc of PR water** (equivalent to 2.5 cm depth irrigation) to the transfer tank and initiate drip wetting. Approximately 6 minutes to apply this amount of water to the surface of the infiltration basket.
13. Allow equilibration time of 9 hours.
14. Transfer **137 cc of PR water** (equivalent to 2.5 cm depth irrigation) to the transfer tank and initiate drip wetting. Approximately 6 minutes to apply this amount of water to the surface of the infiltration basket.
15. Allow infiltration to proceed until completion with extended total time between initiation of wetting and completion of this final step being 60 minutes (start to finish).
16. Transfer **137 cc of PR water** (equivalent to 2.5 cm depth irrigation) to the transfer tank and initiate drip wetting. Approximately 6 minutes to apply this amount of water to the surface of the infiltration basket.
17. Allow infiltration to proceed until completion with extended total time between initiation of wetting and completion of this final step being 30 minutes (start to finish).

Approximately 16 hours were required to complete this sequence of events, after which the soil was removed from the infiltration chamber, the data downloaded and archived, and another run of the study was initiated with a different set of soil samples.

The results of this series of experiments is best illustrated with a selection of graphs, shown as follows (Figures 18-24).

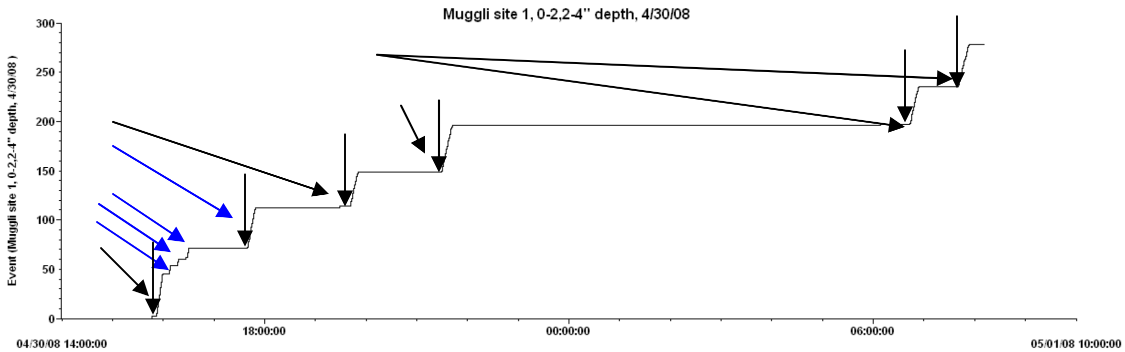


Figure 18. Muggli **Site 1**_0-2_2-4_depth_4_30_08.dtf (in Boxcar Pro 4 directory)

Data presented in Figures 18-24 illustrate cumulative amount of water passing through the soil within the infiltration cylinder (expressed as counts of the tipping bucket) on the vertical axis and accumulated time (absolute) since the start of infiltration on the horizontal axis. Black arrows within the figures identify points in time of initiation of 'pass through' of rain water, while blue arrows within the figures identify points in time of initiation of 'pass through' of simulated irrigation water.

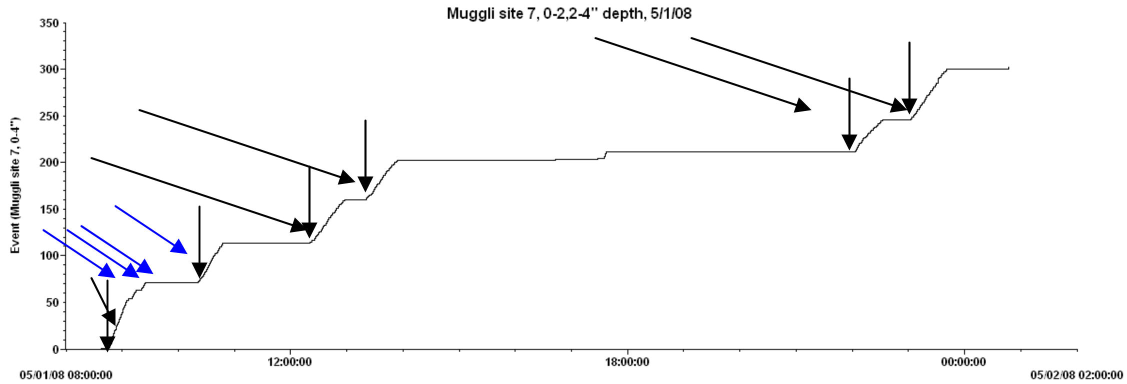


Figure 19. Muggli **Site 7**_0-2_2-4_depth_5_1_08.dtf (in Boxcar Pro 4 directory)

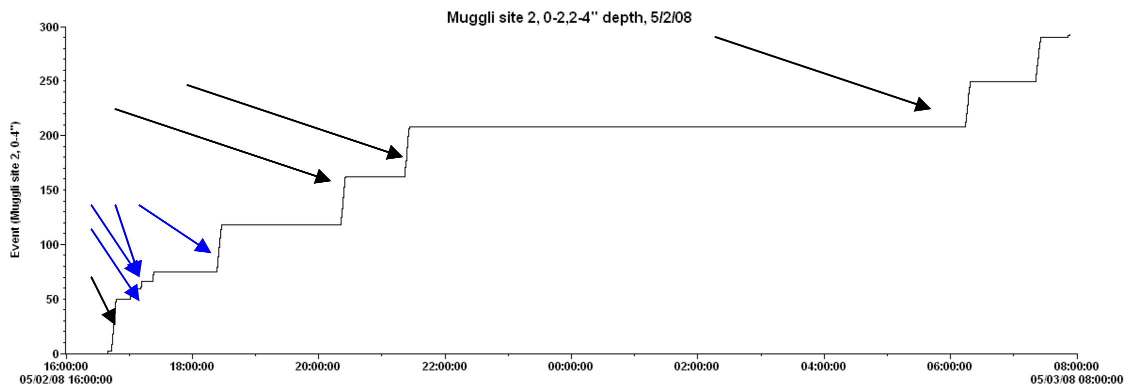


Figure 20. Muggli **Site 2**_0-2_2-4_depth_5_2_08.dtf (in Boxcar Pro 4 directory)

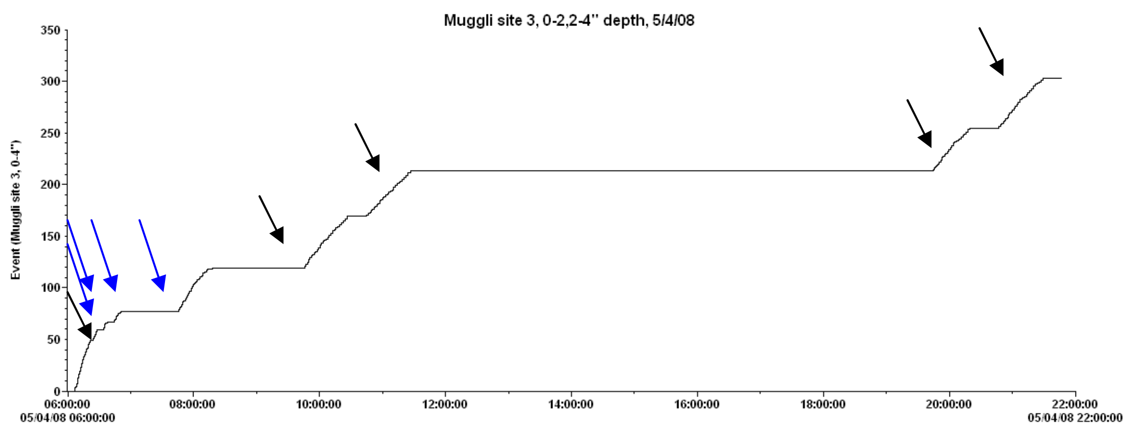


Figure 21. Muggli **Site 3**_0-2_2-4_depth_5_4_08.dtf (in Boxcar Pro 4 directory)

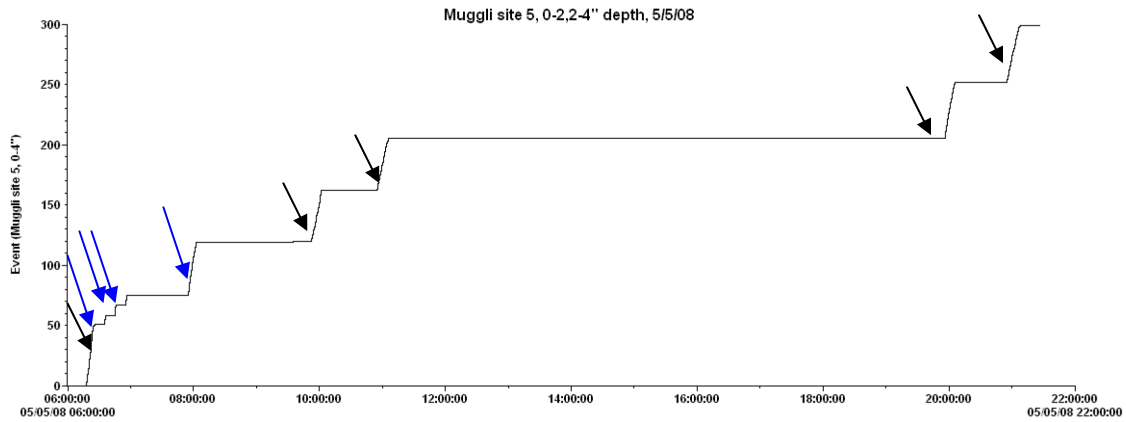


Figure 22. Muggli **Site 5**_0-2_2-4_depth_5_4_08.dtf (in Boxcar Pro 4 directory)

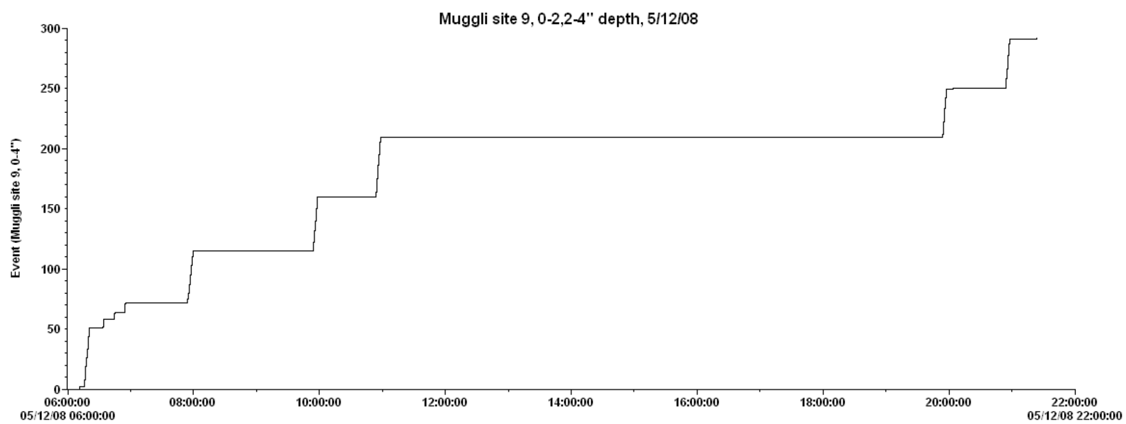
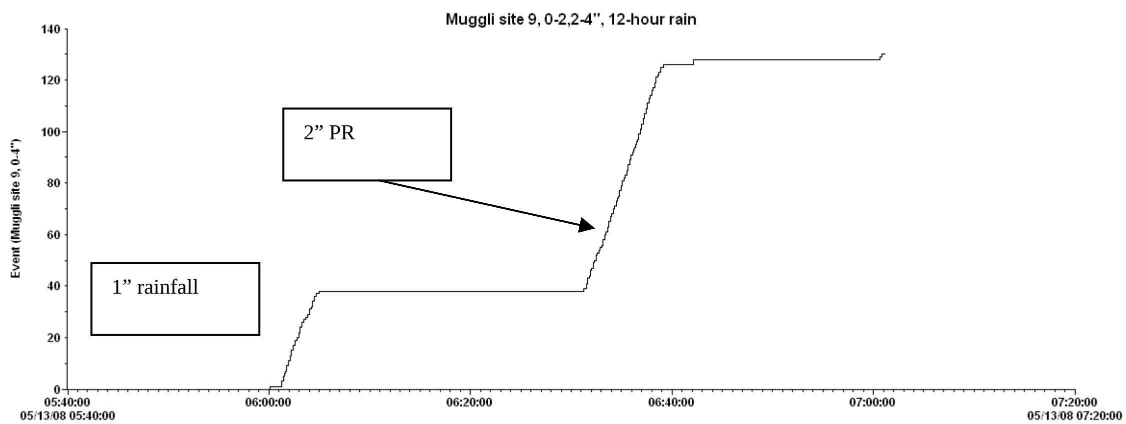


Figure 23. Muggli **Site 9**_0-2_2-4_depth_5_12_08.dtf (in Boxcar Pro 4 directory)

Upon completion of the Site 9 run, the wetted soil was allowed to set for 8 hours, after which a sequence of 1" rain water, 30-minute delay, followed by 2" application of PR water and a 30-minute infiltration measurement period. The following is the output graph from that run. Title is Muggli Site 9_0_2_2-4_12-hour rain.



File is Muggli **Site 9**_0-2_2-4__12-hour rain.dtf (in Boxcar Pro 4 directory)

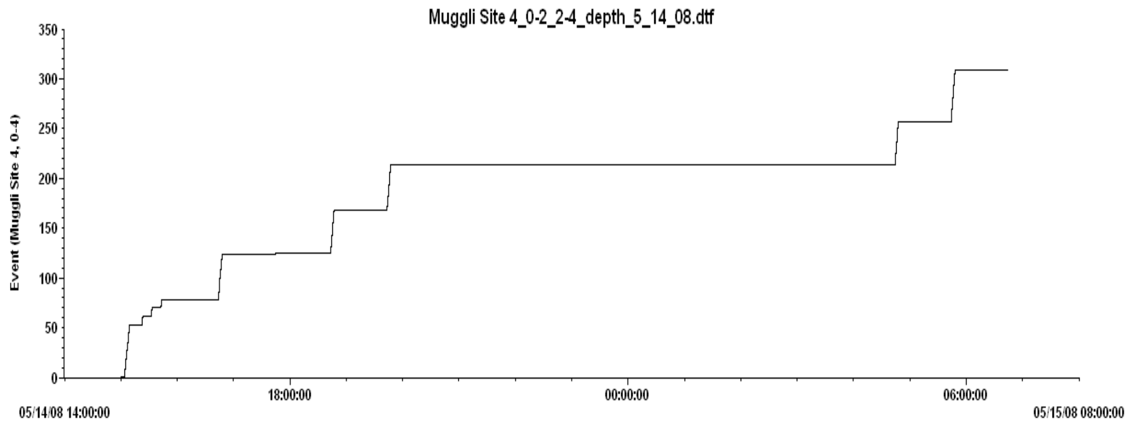


Figure 24. Muggli **Site 4**_0-2_2-4_depth_5_12_08.dtf (in Boxcar Pro 4 directory)

After the completion of these initial infiltration evaluations for the 0-2" + 2'4" soil from each site, the data was retrieved from the respective data logger files. The data were exported to an Excel spread sheet and subsequently converted to infiltration rates. The infiltration rates through the duration of each dosing cycle for each soil site are presented in Table 4. Details of calculations are included in the Appendix.

Table 4. Summary of calculated infiltration rates corresponding to the duration of wetting events associated with intermittent dosing of 0-2" + 2-4" soil from subject site.

Muggli site, 0-2,2-4" run (intermittent dosing).
Summary - all sampling sites
Infiltration rate (in/hr), calculated from HOBO Boxcar data logger x tippng bucket rain gauge

Dosing sequence	Site 1	Site 2	Site 3	Site 4	Site 5	Site 7	Site 9
PR - 5.08 cm	**8.2**	**13.5**	**4.6**	**7.7**	**8.9**	**3.6**	**7.2**
Rain - 2.54 cm	6.1	13.8	1.8	14.8	11.3	2.2	10.7
PR - 2.54 cm	5.0	13.6	1.6	15.7	6.1	1.7	14.6
PR - 2.54 cm	5.0	14.2	1.4	15.7	5.5	1.7	14.9
PR - 2.54 cm	5.1	11.5	1.6	16.1	6.7	1.6	16.0
PR - 2.54 cm	4.5	11.9	1.6	17.5	4.7	1.9	13.6
Average post-rain water dosing	**4.9**	**12.8**	**1.6**	**16.3**	**5.8**	**1.7**	**14.8**
% change: first to last	-45.1	-11.9	-65.2	+78.8	-34.8	-52.8	+105.6

Cumulative equivalent depth water = 17.78 cm

Infiltration rate decreased in soil material from sites 1, 2, 3, 5, and 7 following dosing with the equivalent of 2.54 cm rain water. However, there was little substantial difference between the pre-rain dosing infiltration and the average post-rain dosing infiltration for site 2. In contrast, infiltration rate increased in soil material from sites 4 and 9 following dosing with the equivalent of 2.54 cm rain water. Infiltration with soil material from site 1continued to decrease with each successive dosing with PR water. Referring back to Table 3, Best professional judgement site ranking of risk of dispersion, soil from site 1 was rated as having the greatest risk of dispersion. This was followed in order of greatest to least risk by sites 5, 7, 2, 3, 4 and 9. Soil from sites 4 and 9 were rated as least risk of dispersion and were also the soil materials which actually exhibited an increase in infiltration upon wetting with rain water.

Clearly inherent differences in water transmission characteristics, translated into infiltration capacity, exist among the various soil materials. This is evident from comparison of the overall infiltration patterns of soil from sites 1, 3, 5, and 7 with the overall infiltration patterns of soil from sites 2, 4, and 9.

It is important to realize that the absolute infiltration rate values are of less significance than are differences – either differences among times/events for a specific soil material, or differences among the various soil materials. It should also be recognized that in as much as the infiltration columns were synthesized from bulk soil, naturally-occurring macroporosity was not present in the infiltration columns. Thus, the infiltration values reflect: 1) the ability of the soil, upon wetting to near saturation, to freely drain; and 2) the inherent swelling and dispersion processes of the fine particle material.

In summary, <u>**this first set of controlled experiments**</u> using soil material collected from seven locations within the subject field clearly <u>**demonstrated that intermittent rainfall on smectite-clay dominated soils previously wetted with low EC x low SAR irrigation water can contribute to either swelling or dispersion, resulting in measurable decreases in soil hydraulic transmission properties.**</u> The results also clearly demonstrate that dosing with rainfall can, in some cases, result in increases in soil hydraulic properties. <u>**Soil infiltration rate and near-saturated hydraulic conductivity has the potential to be highly variable within a single field and within a single soil mapping unit,**</u> based on U.S.D.A. Natural Resources Conservation Service web-accessible soil survey data. Thus, <u>**within a single field, substantial variability in crop responsiveness to rainfall following irrigation with water having relatively low specific conductance and relatively low SAR may be encountered.**</u>

A word of caution regarding conclusions needs to be injected here. The reader is advised that the initial assessment of ‘risk of dispersion’ was based on the chemical and physical properties of the soil materials collected from the subject field. Additionally, the physical and chemical properties reflected inherent soil characteristics, including relatively low salinity of all sampled materials, relatively high clay percentages in selected materials (sites 1, 4,5 , and 7), presence of smectite as the dominant clay fraction in all samples, relatively low SARs, and relatively high ESPs in selected materials (sites 1, 2, 5, and deeper depths of sites 7 and 9). Correspondingly, the responses in soil hydraulic conductivity and/or infiltration to either low EC x low SAR irrigation water or rainfall, measured in the subject soils, are more likely a reflection of the inherent chemical and physical properties of the subject soil materials than they are a reflection of the soil material response to the salinity and sodicity of the irrigation water.

A second laboratory experiment consisted of a sequence of 9 consecutive wetting (dosing) events, each equivalent to a 2.54 cm (1-inch) equivalent depth wetting event. The first six events consisted of water having an EC of 1.37 mmhos/cm x SAR=2.8. The seventh event consisted of 'true' rain water, having an EC = 0.06 mmhos/cm x SAR = ND. The last two events were identical to the first six events. This protocol was applied independently to a 3.5 cm depth of soil from the 0-5 cm depth (0-2") of sites 1-5. The objective was to assess: 1) whether infiltration (as measured by hydraulic conductivity) was constant over repeated wetting events with low EC x low SAR water; 2) whether infiltration would change/decrease abnormally from the established pattern, once rain water was introduced; and 3) whether, after the introduction of rain water, infiltration would decrease significantly.

Table 5. Summary of calculated infiltration rates corresponding to the duration of wetting events associated with intermittent dosing of 0-2" soil from subject site; dosing consisted of 9 'equal volume' events, each equivalent to 1-inch depth. Events 1-6, 8-9 consisted of EC=1.37 mmhos/cm x SAR 2.8. Event 7 consisted of 'true' rain water.

Event	inches/hr site 1	inches/hr site 2	inches/hr site 3	inches/hr site 4	inches/hr site 5
2.54 cm PR	6.82	5.95	4.16	9.45	10.03
2.54 cm PR	11.34	4.99	3.88	11.63	9.46
2.54 cm PR	7.90	5.30	2.76	10.92	10.73
2.54 cm PR	4.89	4.59	2.77	10.16	9.15
2.54 cm PR	3.91	3.98	2.78	10.33	7.74
2.54 cm PR	3.77	3.89	2.43	9.56	5.69
2.54 cm Rain	3.58	3.97	2.50	10.98	4.93
2.54 cm PR	3.42	3.82	2.15	10.23	4.15
2.54 cm PR	3.10	2.96	1.49	10.61	3.97

File Muggli 1-events w -1 inch rain insert.xls (soils 1, 2, 3, 4, 5)

In all cases, infiltration (measured as flow-through volume per unit time) decreased following the introduction of rain water (blue arrow, Table 5). However, in all cases, infiltration also decreased between the second wetting event with EC+1.37 mmhos/cm x SAR=2.8 and the wetting event (#6) immediately preceding dosing with rain water, even though water quality was not altered between events 2 and 6 (green arrow, Table 5). Additionally, infiltration decreased between events 6 and 7 (the introduction of rain water) at a rate consistent with the reductions preceding the addition of rain water, and at a consistent rate after the introduction of rain water. These data lead to the conclusion that single rain fall events of the magnitude of this study did not appear to result in abnormally significant decreases in hydraulic conductivity or infiltration, when applied to saturated soils which had been previously wetted with relatively low EC x low SAR water.

Completion of these two sets of controlled infiltration studies subsequently presented the question of whether the measured decreases in hydraulic conductivity of soil material from sites 1, 2, 5, and 7 were a consequence of introduction of rain water or were a consequence of repeated wetting cycles, irrespective of quality of the water applied. There was also the opportunity to question whether the increases in hydraulic conductivity measured for materials from sites 4 and 9 were ‘true’ or merely artifacts of the experimental procedure.

Correspondingly, a third set of controlled infiltration studies was completed, to compare the hydraulic conductivity of soil material under three different dosing regimes, each consisting of five sequential dosing events after initial wetting of the soil. The comparisons included: 1) five equal-volume dosing events with low EC x low SAR water; 2) five equal-volume dosing events with ‘true’ rain water; and 3) five equal-volume dosing events consisting of two dosings with low EC x low SAR water, followed by one dosing with ‘true’ rain water, followed by two dosings with low EC x low SAR water. The objectives of these studies were to: 1) determine whether quality of applied water and/or the event of apply water resulted in a reduction in hydraulic conductivity; and 2) assess the responsiveness of hydraulic conductivity to wetting with low EC x low SAR water following a simulated rainfall event.

Soil infiltration columns were created using soil from 0-2”, 2-4”, 4-6”, and 6-12” increments. A layer of 1.8 cm depth (loose, 10 mm sieved) 6-12” soil was placed in the bottom of the infiltration cylinder. Placed on top of this in sequence were: 1.8 cm depth of 4-6” and 1.8 cm depth of 2-4” soil. On top of this was placed a 1 cm depth of 0-2” soil. The column was gently agitated to insure continuity between the layered soil materials. Infiltrating area = 71.25 cm^2. The infiltration column was placed immediately on top of a tipping rain gauge with measurement capability equivalent to 0.0581 cm equivalent depth per tip from the infiltration cylinder.

PR water with EC 1.37 dS/m, SAR 2.8 (U.S.G.S. Moorhead station, water sourced directly from Powder River immediately downstream of gauging station, 5/15/2008) was applied at a rate of 0.58 cm equivalent depth/minute for four minutes. This rate and volume (equivalent depth) of application did not exceed the dry soil intake rate. The applied water for wetting equated to an applied volume of 166 cc. The infiltration column was then allowed to set/equilibrate for 20 minutes. The value of 166 cc was determined on the assumption that the soil would wet to 40% volumetric water content, which was determined to be 415 cc.

Following the 20-minute equilibration period, a volume of 181 cc of PR water (equivalent depth = 2.54 cm) was applied to the surface of the soil in the infiltration cylinder. This volume was applied at a rate of 55.7 cc/minute (equivalent to 0.78 cm equivalent depth/minute). This rate of application exceeded the wetted soil infiltration rate and water ponded to approximately 1 cm depth within the column. The ponded water was allowed to infiltrate until all water had infiltrated the surface and/or the rain gauge no longer indicated drainage into the tipping bucket.

Once infiltration/saturated flow-drainage had ceased, an additional 181 cc of PR water was applied to the surface of the infiltration column, using procedure identical to that for the initial dosing with PR water. Again, infiltration/drainage rate was measured until drainage ceased.

Once infiltration/saturated flow-drainage had ceased, 181 cc of ‘true’ rainwater was applied to the surface of the infiltration column, using procedure identical to that for the initial dosing with PR water. Again, infiltration/drainage rate was measured until drainage ceased.

The process was then repeated a fourth and fifth time, using two sequential doses of 181 cc PR water, each applied by the same process as previously described.

Upon completion of this experiment, the entire experiment (including construction of a new infiltration column) was repeated, with identical procedure except the only water used was PR water, i.e., the 181 cc rain water dosing was replaced with a 181 cc PR water dosing. Finally, the experiment was repeated a third time, in which case the only water used was rain water, i.e., all dosing with PR water was replaced with dosing with rain water. A summary of results is presented in Table 6.

In the circumstance of site 1, wetted with 1-inch rainfall event following two 1-inch irrigation events: hydraulic conductivity progressively decreased from the onset of wetting through the duration of measurement. Inclusion of a 1-inch rainfall event following two 1-inch irrigation water events resulted in a slightly greater decrease in hydraulic conductivity in the subsequent events than was observed in the measurements preceding the rainfall event. When the soil from site 1 was wetted with five successive 1-inch irrigation events: hydraulic conductivity decreased progressively throughout the wetting sequence. The relative magnitude of decrease over the duration of the wetting events was less than the magnitude of the decrease observed when rainfall was introduced after the second irrigation event. Finally, in the case of site 1 being wetted with five successive 1-inch rainfall events: hydraulic conductivity was substantially restricted during the initial wetting and throughout the duration of the wetting events. By completion of the third wetting event with rain water, the hydraulic conductivity had decreased to essentially zero flow-through.

As was previously stated, the reader is cautioned not to consider absolute hydraulic conductivity values but rather consider valid comparisons and evaluations to be a comparison of hydraulic conductivity among wetting events of a single soil column. The valid evaluation is: 1) the degree to which hydraulic conductivity decreases across wetting events; and 2) the degree to which the pattern of decrease varies among wetting regimes.

Table 6. Summary: comparison of infiltration rates of packed soil columns dosed with either: 1) five 1-inch wetting events, the 1st, 2nd, 4th, and 5th being 'true' rain water and the 3rd being water with EC of 1.37 mmhos/cm x SAR=2.8; 2) five 1-inch wetting events, all consisting of water with EC of 1.37 mmhos/cm x SAR=2.8; or 3) five 1-inch wetting events, all consisting of 'true' rain water.

Muggli site, 0-12" run, 5-event dosing; w/ and w/o rainfall interjection

Note: The valid evaluations/comparison in this summary table are only: 1) within an individual column of a specific site x soil combination, i.e., the response of site 1 soil to introduction of rain water or rain water as the only wetting source, indicated by the red arrow; or 2) as a general comparison of responsiveness among the various sites, i.e., comparing the relative hydraulic conductivity of site 1 with that of site 2, 4, 5, or 7.

Site 1

w/2.54 cm rain	w/all PR	w/all rain
0.74	0.94	0.24
0.44	0.68	0.05
Rain →0.37	0.43	< 0.05
0.22	0.38	< 0.05
0.1	0.34	< 0.05

Site 2

w/2.54 cm rain	w/all PR	w/all rain
3.83	12.79	15.82
3.94	8.51	6.77
Rain →3.33	7.79	4.98
3.05	6.22	3.39
1.97	5.87	2.74

Site 5

w/2.54 cm rain	w/all PR	w/all rain
2.69	4.35	4.01
1.09	4.28	3.73
Rain →0.57	4.14	3.25
0.48	4.01	3.02
0.42	3.82	2.81

Site 4

w/2.54 cm rain	w/all PR	w/all rain
13.60	2.65	18.72
10.93	0.97	15.96
Rain → 6.74	2.16	13.17
7.71	1.30	15.58
7.81	0.77	13.46

Site 7

w/2.54 cm rain	w/all PR	w/all rain
14.65	12.04	12.09
14.08	11.85	11.85
Rain → 13.86	11.76	11.71
13.43	11.52	11.35
13.05	11.43	11.08

File: Muggli 1-inch rain control study.xls

In the column consisting of soil from site 2, hydraulic conductivity progressively decreased from the onset of wetting through the duration of measurement. Inclusion of a 1-inch rainfall event following two 1-inch irrigation water events resulted in no apparent change in the pattern of decrease in hydraulic conductivity in the subsequent events than was observed in the measurements preceding the rainfall event. In the circumstances of wetting with five successive 1-inch irrigation events, hydraulic conductivity decreased progressively throughout the wetting sequence. The relative magnitude of decrease over the duration of the wetting events was less than the magnitude of the decrease observed when rainfall was introduced after the second irrigation event. Similarly, hydraulic conductivity was significantly reduced during the initial wetting and continued to progressively decrease throughout the duration of the wetting events with only rain water. In contrast to the soil from site 1, this soil maintained good conductivity (for the most part) under all circumstances of wetting, although conductivity did decrease in all repeated wetting circumstances.

Hydraulic conductivity of soil from site 4 progressively decreased from the onset of wetting through the 1-inch rainfall wetting. Following the 1-inch rainfall wetting, the hydraulic conductivity actually increased – although likely not significantly. It appeared that hydraulic conductivity stabilized/established equilibrium following the rain water wetting event. When subjected to five successive 1-inch irrigation events, hydraulic conductivity was relatively low with no consistent pattern throughout the wetting sequence. The relative magnitude of all measurements of hydraulic conductivity during repeated wetting with rain water was substantially less than the hydraulic conductivity measured under other wetting regimes. It appeared as though this soil was significantly affected by rain water additions.

Inventory and assessment of irrigable, smectite-dominated clay soils along the Tongue River in Montana

The U.S.D.A. Natural Resources Conservation Service Web Soil Survey was accessed to compile an inventory of irrigable soils along the Tongue River corridor (http://websoilsurvey.nrcs.usda.gov/app/) from Miles City to immediately below the confluence of Tongue River with Circle L Creek. The latter is located approximately 6 miles upgradient of the T & Y irrigation district diversion on the Tongue River. This river corridor selection, although arbitrary, was assumed to be representative of irrigated acreage along the lower reach of the Tongue River, while also encompassing a significant portion of the irrigated acreage of the T & Y irrigation district.

Tools available via Web Soil Survey allow for inventory of manually selected shape files of areas of interest, with responses to queries including delineation of uniquely identifiable soil mapping units, irrigable parcels, and acreages of various soil mapping units within queried areas. A complete listing of map units, acreages in areas of interest, and parcel delineations is included in the appendix.

For purposes of the investigation, a summary of acreages encompassed by soil map units comprised of or representing soils containing 28% or more clay (on a mass basis), having slopes not exceeding 2%, or consisting of other soil mapping units inclusive of the subject field was compiled. The 28% clay cut-off resulted in inclusion of soils with textural classifications of silty clay, silty clay loam, clay loam, sandy clay, and clay. The 2% slope factor was used as a criteria for land parcels suitable for flood or other surface irrigation. Although this threshold clay percentage was arbitrary and the inclusion of soil mapping units also found in the subject field was subjective, it did provide a mechanism for assessment of the potential acreage along the Tongue River and within the T & Y irrigation district that might be subject to rainfall-induced dispersion and/or subject to the circumstances reported in the subject field.

The total acreage within the area of interest previously described amounted to 6,315 acres. Approximately 1,636 acres were identified was having more than 28% clay, while an additional 1,664 acres consisted of other mapping units identified in the subject field as well. Thus, in total approximately 3,300 acres of the 6,315 acres within the area of interest along the Tongue River corridor, exhibited soil physical properties similar to those measured on soils from the subject field.

It is reasonable to assume that the clay fraction of these soils in the area of interest is smectite-dominated, as was the case with the soil of the subject field. However, some caution needs to be exercised in assuming that the soils of the area of interest along the Tongue River will respond similarly to the incident reported in 2006. As controlled laboratory studies and detailed chemical analyses have shown, considerable variability can be encountered, both with respect to soil responsiveness to rainfall and with respect to inherent soil physical and chemical conditions within a single irrigated field.

The predominant soil mapping unit of the subject field was identified as ‘Kobase silty clay loam, 0-2% slope’. This particular mapping unit constituted 514 acres of the area of interest along the

Tongue River. The other predominant soil mapping unit of the subject field was identified as 'Yamacall loam, 0-2% slope'. This mapping unit constituted 1,664 acres of the area of interst along the Tongue River. In combination, these two mapping units amounted to 2,178 acres (34%) of the acreage within the area of interest along the Tongue River corridor down gradient of confluence with Circle L Creek.

Appropriateness and suitability of irrigation water quality standards specific to the Powder River Basin, established in 2003 by the Montana BER

In April, 2003, the Montana Board of Environmental Review adopted numeric, in-stream standards for salinity and sodicity of the Powder and Tongue Rivers and tributaries. The following is a summary of those standards, specific to the Powder and Tongue Rivers:

Irrigation season:
- Powder River: maximum EC = 2.5 dS/m; maximum SAR = 6.0
- Tongue River: maximum EC = 1.5 dS/m; maximum SAR = 4.5

Non-irrigation season:
- Powder River: maximum EC = 2.5 dS/m; maximum SAR = 9.75
- Tongue River: maximum EC = 2.5 dS/m; maximum SAR = 7.5

Appropriateness can be defined as being suitable for a particular condition; the extent to which the outcomes match the needs of the stakeholders. Correspondingly, suitability can be defined as the quality of having the properties that are right for a specific purpose; the appropriateness of a strategy, taking into account the ability and objectives of the stakeholder.

With regard to appropriateness and suitability of irrigation water quality standards, the desired outcomes or conditions are: 1) sustainability of suitability of irrigated land parcels; 2) sustainability of irrigated crops (perennial grasses and forages); and 3) ability to enhance crop production. In the context of the standards adopted by the Montana Board of Environmental Review, salinity (expressed as EC) was addressed in the context of adverse impact of salinity on sustainability of irrigated crops and ability of irrigation water to enhance crop production. Sodicity (expressed as SAR) was addressed in the context of potential for adverse impact of sodicity on sustainability of irrigated land parcels.

Field and laboratory studies and analyses specific to the reported crop loss and subject field of this report did not provide direct evidence to the appropriateness or suitability of the standards of salinity and sodicity established by the Montana Board of Environmental Review for the Tongue and Powder Rivers. Although crop loss and plant death due to dispersion of smectite-clay dominated soils likely occurred, **the soil dispersion did not appear to be a consequence of irrigation with water sourced from the Tongue River.** Dispersion appeared to be a consequence of a combination of inherent soil physical and chemical properties and an extended period of rainfall, followed by elevated evaporative demand to a first-year alfalfa planting. Soil dispersion and crop death was limited to areas of the field where the inherent clay content ranged from nearly 40% to more than 60%, the exchangeable sodium percentage ranged from 12.5% to

33.7% in the sampled depths, and cation exchange capacity averaged more than 35 meq/100 g dry soil. The dominant clay fraction was smectite. Thus, the circumstances of the reported crop loss do not provide an opportunity for direct assessment of the appropriateness and suitability of in-stream water quality standards of salinity and sodicity for the Tongue and Powder Rivers.

The particular circumstances of this reported crop loss and the controlled laboratory studies of hydraulic conductivity do provide evidence of the susceptibility of smectite-dominated soils to dispersion, both as a consequence of rainfall and irrigation-applied water. **Under controlled laboratory conditions, soils having ESPs of 7.25, 8.12, and 8.95% exhibited reductions in hydraulic conductivity upon wetting with either EC=1.37 x SAR 2.4 water or 'true' rain water. These ESPs correspond (approximately) to applied water SARs of 3.5 to 4.5.**

Numerous references can be found in the scientific literature pertaining to critical or threshold values of SAR of irrigation water and soil ESP values conducive to rainfall-induced dispersion. Shainberg et al. (1981), evaluating changes in hydraulic conductivity and clay dispersivity of a fine-loamy, mixed, thermic Typic Haploxerolf, reported that **when the soil was wetted with distilled water (simulating rainfall), clay dispersion occurred and hydraulic conductivity decreased at ESP values as low as 1 to 2%.** They further reported that clay-dominated, mineral soils, with low rates of mineral dissolution, are likely to be susceptible to dispersion and decreased hydraulic conductivity even at low ESP values.

Shainberg et al. (1981) observed that clay dispersion and reductions in soil permeability took place under circumstances of intermittent rainfall, even at low ESP values. In some circumstances of wetting with rain water, clay dispersion and hydraulic conductivity reductions occurred at an ESP as low as 1 to 2 (Shainberg et al., 1981). Correspondingly, Suarez et al. (2006) reported that in a loam soil having smectite as the dominant clay fraction, the adverse impacts of sodium on infiltration were evident when SAR exceeded 2, while for the clay soil adverse impacts occurred when SAR exceeded 4. Reductions in infiltration were evident during the irrigation and/or rain events, with lower infiltration during rain simulations. These results are consistent with those reported in the present studies.

From the perspective of salinity of irrigation water and sustainable irrigation, Schafer (1983a), among others, reported irrigation water with an ECw of 0.75 to 3.0 mmnos/cm as presenting 'increasing problem' from the perspective of sustainable, long-term irrigation. Correspondingly, irrigation water with an ECw < 0.2 mmhos/cm, combined with an SARadj > 8 is categorized as 'increasing problem' or 'severe problem'. Typically, the SARadj will be substantially greater than the unadjusted SAR in prairie streams and rivers of eastern Montana. **Schafer further refines the 'suggested range in irrigation water EC and SAR as 0.5 to 2 mmhos/cm and < 6, respectively, for silty clay loam soils.** Quoting from Schafer (1983b), "Use of moderately saline irrigation water can quickly lead to hazardous accumulations of salt in the soil profile…. **irrigation water with an electrical conductivity (EC) of 2 mmhos/cm, which is at the upper end of salt concentration suitable for long-term irrigation…."**

Supporting Literature Review

Key points substantiated by literature review:

- Elevated sodicity of soil solution or irrigation water can result in a significant decrease in soil hydraulic conductivity.
- Elevated soil solution or irrigation water salinity can mitigate (offset) the adverse effect of elevated sodicity on soil hydraulic conductivity, i.e., elevated salinity promotes fine particle flocculation.
- Structure of sodic soil can be maintained if salinity level is maintained above minimum threshold level.
- Flocculated, sodic soil will slake and disperse and soil structure will deteriorate if the salinity is decreased to a concentration below the minimum threshold level.
- Sodium adsorption ratio (SAR) reflects the risk of dispersion resulting from applied water and/or soil solution composition; ESP provides the most reliable index of soil inherent dispersion risk or potential for dispersion.
- Addition of distilled water or rainfall to a flocculated, sodic soil, can result in sufficient decrease in salinity to result in fine particle dispersion and deterioration of soil structure.
- Mineral soils which release salt during leaching are likely to be resilient to the dispersive effects of sodium as long as ESP was maintained at < 10%.
- 2:1 expansive clay-dominated, mineral soils (smectite), with low rates of mineral dissolution, are likely to be susceptible to dispersion and decreased hydraulic conductivity even at low ESP values.
- Surface soils, when leached with rainwater, may be especially susceptible to dispersion and reduced hydraulic conductivity at low levels of exchangeable sodium.
- Probability of dispersion increases under conditions of intermittent rainfall.
- Soil dispersion has been documented under conditions of exchangeable sodium percentage as low as 1-2, and given conditions of salinity as low as 3.0 meq/liter (~ 0.3 dS/m), decreases in hydraulic conductivity and increases in clay dispersion occurred if the exchangeable sodium percentage exceeded 12.

EC x SAR and dispersion

The first systematic investigation into the effects of salts on permeability was made by Gedroiz (1924), wherein he reported that the permeability of soil is greatly reduced by replacing naturally occurring ions (chiefly Ca^{+2}) with Na^{+}. Following up on the work of Gedroiz, Kelly (1951) proposed that adsorbed cations, soluble salts and electrolytes present in irrigation water influence the effects of sodium on soil permeability to water. High concentrations of adsorbed calcium and magnesium reduce the effects of sodium on infiltration. Kelley further showed that in the case of soils containing both soluble salts (reflected in electrical conductivity of saturated paste extracts - EC_e) and adsorbed sodium (reflected in exchangeable sodium percentage – ESP), permeability decreases as the soluble salts are leached, i.e., EC or TDS decreases, due to deflocculation (dispersion) of the soil. Conversely, high electrolyte concentrations (reflected in relatively high

EC) in irrigation water aid in maintaining permeability. Although water with high sodium content, rendering the electrolyte concentration high, may increase permeability, over time permeability will decrease due to sodium adsorbing onto the soil colloids.

Since the early work of Gedroiz and Kelly, the fact that soil aggregate stability can be affected by soil solution electrolyte concentration – sodium adsorption ratio (SAR) relationship has been well publicized (Abu-Sharar et al., 1987; Cass and Sumner, 1982; Emerson and Bakker, 1973; Frenkel et al., 1978; McNeal and Coleman, 1966; Quirk and Schofield, 1955; Rhoades and Ingvalson, 1969; Ayers and Westcot, 1976; Mace and Amrhein, 2001; Shainberg et al., 1981; Yousaf, 1983; Oster and Schroer, 1979; Browning et al., 2007).

Elevated sodicity in irrigation water can adversely affect soil structure, thereby potentially influencing water infiltration, nutrient supply, and aeration (U.S. Salinity Laboratory Staff, 1954). However, there is well-known **complimentary relationship between salinity and sodicity, with respect to soil physical properties: presence and/or increases in soil solution or saturated paste extract EC can reduce the negative effects of Na^+ on the physical degradation of a soil** (Shanmuganathan and Oades, 1983, Van Olphen, 1977, Arora and Coleman, 1979, Sumner et al., 1998). A sodic soil can maintain its structure if the salinity level is maintained above a so-called threshold electrolyte concentration (TEC). In fact, a soil with high EC and SAR will maintain good physical structure (Shanmuganathan and Oades, 1983; Agassi et al., 1981). Circumstances which maintain or increases EC help to meet the TEC requirement for maintaining good soil structure at a given SAR. If salinity is maintained at or above the TEC value for a specific material, the physical condition of the material will be maintained in a flocculated state, no matter how high the SAR (Sumner et al., 1998; Agassi et al., 1981).

Correspondingly, an elevated EC or an increase in EC produced by evapoconcentration at the soil surface can counter the adverse impacts of Na^+, while helping maintain soil structure. However, if the salinity level is low or allowed to decrease after establishment of an equilibrium salinity – sodicity combination that promotes flocculation, a sodic soil will slake and disperse and soil structure will deteriorate. For example, Shainberg et al. (1981) evaluated changes in hydraulic conductivity and clay dispersivity of a fine-loamy, mixed, thermic Typic Haploxerolf as a function of irrigation water salinity and SAR. They reported that when the soil was wetted with distilled water (simulating rainfall), clay dispersion occurred and hydraulic conductivity decreased at **ESP values as low as 1 to 2%**. (Typically, an ESP of 1-2% corresponds to an SAR of 0.75 to 1.5.) Thus, it is reasonable (and substantiated) to conclude that application of irrigation water of low salinity, i.e., relatively low salt concentration, expressed as EC, or rainfall to soil materials that have elevated SAR can result in clay dispersion (Abu-Sharar et al., 1987; Rengasamy and Olsson, 1991; Sumner et al., 1998). In addition, mechanical forces resulting from raindrop impact, the flow of water at the surface due to flooding, or the use of farm equipment can enhance clay dispersion.

The preceding leads to the conclusion that it is difficult to estimate the impact of high or low SAR values of irrigation waters on the physical state of a soil without evaluating the EC of the system (Shanmuganathan and Oades, 1983). This was first demonstrated by Quirk and Schofield (1955). Their work demonstrated that soil materials with an ESP of 40 maintained a stable permeability with an electrolyte concentration of EC ≈ 2.1 dS/m (approximately 1,344 mg/l solute concentration). Shainberg et al. (1981) proposed that mineral soils, which readily release salt during leaching with distilled water (assumed representative of rainfall conditions) would not likely follow this response condition as long as ESP was maintained at < 10%. Conversely, clay-dominated, mineral soils, with low rates of mineral dissolution, are likely to be susceptible to dispersion and decreased hydraulic conductivity even at low ESP values. They further proposed that "surface soils, when leached with rainwater, will be especially susceptible (*to dispersion and reduced hydraulic conductivity*) at such low levels of exchangeable Na."

McNeal and Coleman (1966) found that typical arid land soils having clay mineralogy dominated by 2:1 layer silicates, but only moderate amounts of montmorillonite, can tolerate ESP values of 15 or greater before serious reductions in hydraulic conductivity occur, if the salt concentration of the solution exceeds 3 mmol L^{-1} (~ EC= 0.3 dS/m; 0.3 mmhos/cm; electrolyte concentration of approximately 200 mg/l). In contrast, irrigation waters generally have low EC values and often do not meet the TEC required to maintain soil structure in the presence of exchangeable Na^+.

Correspondingly, increases in or elevated EC may affect crop performance. Collectively, if irrigation is not managed properly, salt accumulation in the root zone can result in high Na concentrations, elevating SAR (Balks et al., 1998; Halliwell et al., 2001; Sparling et al., 2001), increasing the risk of soil dispersion, reducing hydraulic conductivity and infiltration capacity (Magesan et al., 1999), and reducing osmotic potentials leading to drought-like conditions for plants (Shani and Dudley, 2001). Alfalfa is known to have a low tolerance for salinity, with a threshold value of 2.0 dS m^{-1}; however, sensitivity of alfalfa to salinity is cultivar specific (Kotuby-Amacher et al., 2000).

Note: within the context of this review, EC is generally expressed as dS m^{-1}. Numerically, dS m^{-1} is equivalent to mmhos cm^{-1}. Thus, a threshold value of 2.0 dS m^{-1} is equivalent to a threshold value of 2.0 mmhos cm^{-1}. For general discussion purposes, EC can be related to electrolyte concentration by the approximation: mg l^{-1} = EC (dS m^{-1}) x 640.

In natural soil environments, complex clay systems are bound together into aggregates with silt and sand particles by inorganic and organic compounds. The complex relationship between soil salinity, sodicity, and soil physical property behavior is a function of the diffuse double layer associated with individual soil particle surfaces. Rengasamy and Sumner (1998) have developed a model describing the processes that take place during the wetting of a dry soil aggregate. This model and the relationship between soil solution salinity and sodicity is dependent on the concept of diffuse double layer (Abu-Sharar et al., 1987, Rengasamy and Olsson, 1991, Rengasamy and Sumner, 1998). Their model considers the influences of salinity and sodicity on the physical nature of natural soil systems. As dry aggregates are wetted, hydration forces (forces of wetting) become important. The stability of aggregates, and hence the pore systems, depends on attractive and repulsive forces resulting from intermolecular and electrostatic interactions between the soil solution and soil particles (Rengasamy and Olsson, 1991). In general, if clay particles are saturated with Ca^{2+} or Mg^{2+}, aggregates are held together by these cations. If the clays are saturated by monovalent cations such as Na^+, the clay particles may be dispersed depending on solution ionic strength, e.g., EC.

Rengasamy and Sumner (1998) indicated that spontaneous dispersion takes place when sodic clay is impacted with water of very low electrolyte concentration. Correspondingly, the chemistry of calcium (Ca) and sodium (Na) comes into play in the understanding of effects of irrigation water salinity on soil dispersion. Under circumstances of abundance of carbonate/bicarbonate in the soil or in aqueous systems, it is frequently the case that calcium in solution combines with free carbonate/bicarbonate, forming relatively insoluble calcium carbonate – thus simultaneously lowering the soil solution EC and increasing the SAR, thereby increasing the deleterious effects of Na on soil (Ayers and Westcot, 1994; Halliwell et al., 2001).

Oster and Schroer (1979), studying the infiltration rate of undisturbed loam soil columns, found that the effects of the chemistry of the applied water were far greater than expected. When the ESP of the surface soil water was 8, infiltration rates decreased from 15 to 1 mm/hour as the concentration of the irrigation water decreased from 28 to 8 meq/liter (approximately equal to a decrease in EC from 2.8 to 0.8 dS/m; 2.8 to 0.8 mmhos/cm). Comparable reductions in saturated hydraulic conductivity of saturated soils with an ESP of 10 occurred when the concentration of percolating solution decreased below 2 to 3 meq/liter (approximately equal to a solution EC of 0.2 to 0.3 dS/m) (Shainberg et al., 1981).

Shainberg et al. (1981) reported: "It is evident that both the electrolyte concentration of the applied water and the ESP of the soil have a very pronounced effect on the infiltration rate of the soil. The final infiltration rate (IR) of the soil exposed to distilled water rain was independent of the ESP of this soil….. It is concluded that, when distilled water is applied, even low ESP values (less than/equal to 6.4) are enough to cause dispersion, crust formation, and a very sharp decrease in IR. Conversely, when water of EC 5.6 mmhos/cm is used, the concentration of electrolyte is so high that only limited clay dispersion is possible, independent of the soil ESP (at ESP less than/equal to 26), and the final IR is maintained at a relatively high value.

"When distilled water is applied to a soil, even with low levels of exchangeable sodium, chemical dispersion of the soil clay also occurs, the dispersed clay particles are washed into the soil with the infiltrating water, and the pores immediately beneath the surface become clogged. In the study reported by Agassi et al. (1981) …. the final infiltration rate dropped to values which were 0.16 of those obtained with the most saline water."

These same researchers additionally cited studies of Felhendler et al (1974), who measured the hydraulic conductivity of two soils (a sandy loam and a silty loam, both containing montmorillonite, i.e., smectite clay) as a function of the SAR and EC of the percolating solution, and found that **both soils were only slightly affected by the SAR of the percolating solution up to SAR 20 as long as the EC of the percolating solution exceeded 10 meq/l (i.e., > 1.0 mmhos/cm or 1.0 dS/m). (meq/l(mmolc/L) / 10 = EC (dS/m or mmhos/cm) for 0.1 < EC < 5 dS/m.)** However, when the percolating salt solution was replaced by distilled water, simulating rainfall, the response of the two soils differed drastically. The **hydraulic conductivity of the silty soil dropped to 42 and 18% of the initial value for soils with ESP values of 10 and 20, respectively**.

Intermittent applications of rainwater may also lower the electrolyte concentration below the threshold value. Shainberg et al. (1981) observed that clay dispersion and reductions in soil permeability took place under circumstances of intermittent rainfall where little soil swelling was expected, even at low ESP values. When the salt concentration was 3.0 meq/liter (~ 0.3 dS/m), decreases in hydraulic conductivity and increases in clay dispersion occurred if the ESP exceeded 12. Conversely, in distilled water (*considered analogous with rainfall*), clay dispersion and hydraulic conductivity reductions occurred at an ESP as low as 1 to 2 (Shainberg et al., 1981).

One of the most recently published studies investigating the interaction between EC, SAR, and rainfall was that of Suarez et al. (2006). These researchers examine water infiltration into loam and clay soils irrigated at EC = 1.0 and 2.0 dS m^{-1} at SAR of 2, 4, 6, 8, and 10 in a management system with alternating (simulated) rain and irrigation and drying between irrigations. For the loam soil the adverse impacts of sodium on infiltration were evident when SAR exceeded 2, while for the clay soil adverse impacts occurred when SAR exceeded 4. In each soil the SAR behavior was similar for either EC, i.e., 1.0 or 2.0 dS m^{-1}, indicating that in this range, EC did not influence infiltration. Reductions in infiltration were evident during the irrigation and rain events, with lower infiltration during rain simulations. These results show a greater sensitivity to SAR than indicated in laboratory column studies and existing water quality criteria.

3.0 meq/liter is approximately equal to 70 ppm Na, 60 ppm Ca, 37 ppm Mg, or 125 ppm sodium bicarbonate. This would be comparable to an EC of 0.3 dS/m (or mmhos/cm).

Physical effects of rainfall

In addition to the relationship between soil, soil solution, irrigation water electrochemical signature and soil hydraulic properties, consideration needs to be given to the physical effects of rainfall and irrigation water additions. Formation of a seal at soil surfaces exposed to the beating action of raindrops is a common phenomenon in many cultivated soils, worldwide. Surface seals are thin (<2 mm) and are characterized by greater density, higher shear strength, finer pores, and lower saturated hydraulic conductivity, compared with those of the bulk soil (McIntyre, 1958; Bradford et al., 1987).

Seal formation is caused by two mechanisms: (i) a physical break-down of soil aggregates caused by the mechanical impact of waterdrops; and (ii) a physico–chemical dispersion and movement of clay particles into a region 0.1 to 0.5 mm deep, where they lodge and clog the conducting pores (McIntyre, 1958; Agassi et al., 1981). The two mechanisms act simultaneously and the former enhances the latter.

Mamedov et al. (2000) report: “The formation of a seal at soil surfaces exposed to beating action of raindrops is a common phenomenon”. They further reported that seal formation at soil surfaces is significantly affected by raindrop kinetic energy (KE). They hypothesized that deterioration in permeability of irrigated soils is affected, among other things, by raindrop KE. The effects of four simulated raindrop KE levels (3.6, 8.0, 12.4, and 15.9 kJ m^{-2}) on infiltration of four smectitic soils were studied. Irrigation (droplet) water quality studied was either fresh water (FW) or wastewater effluent (high SAR). At the lowest KE (3.6 kJ m^{-2}; least raindrop impact), final infiltration rates (IR) for fresh water-irrigated samples were in the range of 9 to 14 mm h^{-1} and were significantly greater than the corresponding infiltration rates for the effluent-irrigated samples, suggesting that seals were not fully developed at this low KE and that the irrigation water type played a major role in determining soil permeability. At high KE (15.9 kJ m^{-2}; greatest raindrop impact), the differences between the final infiltration rates of fresh water-irrigated and effluent-irrigated samples of a given soil were small (<1.1 mm h^{-1}), suggesting that **at high KE, the effect of drop impact overshadowed the effects of water quality on the final infiltration rate.**

In unstable soils, a seal may be formed under low-KE waterdrops by the process of fast wetting and aggregate slaking (Le Bissonnais, 1990). In research similar to that reported by Mamedov et al. (2000), Betzalel et al. (1995) found that **as raindrop kinetic (impact) energy increased, infiltration rate decreased, irrespective of the rainfall amount.** Shainberg and Singer (1988) observed that sodic soils were more susceptible to sealing by low-KE raindrops than were calcium-dominated soils.

Relationship between source water quality and soil electrochemical properties

"Irrigation with water of a moderate sodium adsorption ratio (SAR~ 6) leads to soils with exchangeable sodium percentages (ESPs) of a similar value" (USSLS, 1954). The hydraulic properties of soils having such an ESP are not likely to be affected during the irrigation season, but could deteriorate when these soils are leached with distilled water (DW), used to simulate rain water."

The Effect of Structural Instability on the Soil's Field Characteristics

When a soil slakes under rapid wetting followed by dispersion, it will result in the formation of a surface seal with a reduced hydraulic conductivity. This in turn will give rise to reduced rates of infiltration, redistribution and evaporation from the soil (So and McKenzie 1984).

"A consequence of the reduced rate of redistribution or drainage of the surface soil is temporary surface waterlogging, which is not conducive to seed germination and generally delays farm operations. Waterlogging is associated with a lack of oxygen needed for seed respiration. Hence an extended period of waterlogging may result in excessive imbibition of water without adequate embryo development, resulting in a failure to germinate, known as 'seed bursting'.

The high water contents during periods of waterlogging at the suface are followed by high initial rates of evaporation (stage 1 evaporation), similar to evaporation from a free water surface. However, if the hydraulic conductivity of the soil is very low and unable to match the rate of water loss, the surface will dry rapidly followed by shrinkage and a breaking away of the dry surface into crusts. This is generally limited to a few centimeters in thickness."

"A surface crust or hardsetting surface represents a dry surface mulch where water movement is slow and predominantly in the vapour phase (advanced stage 2 evaporation).

Therefore the rate of evaporation is reduced considerably, resulting in a slower rate of drying. Consequently the subsoil tends to remain wet….”

Referring to Figure 2 (adapted from Shainberg et al. 1971 and Shainberg and Caiserman 1971) “….the ……. Ca-dominated clay systems are essentially unaffected until Na reaches a threshold of about 7-20% of the total cation suite, i.e., ESP = 7-20%, (Shainberg *et al.* 1971), depending on the prevailing overburden pressure. **When the exchangeable sodium percentage (ESP) exceeds the threshold value, swelling increases significantly with an increase in ESP.** In contrast, small increases in **ESP tend to have a large effect on the hydraulic conductivity of the clay paste and the decrease starts from a value of zero ESP** (Shainberg and Caiserman, 1971).

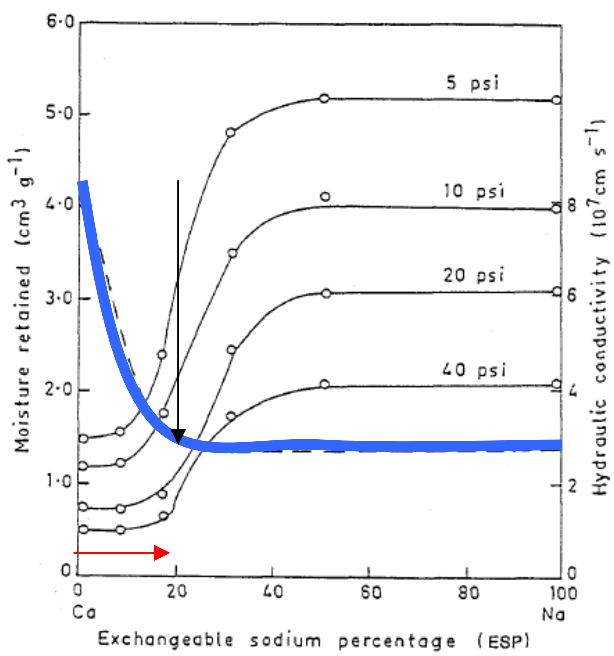


Fig. 2. The moisture content (swelling) in solid lines and the hydraulic conductivity (blue line) of montmorillonite as affected by exchangeable sodium percentage (adapted from Shainberg et al. 1971 and Shainberg and Caiserman 1971).

Effect of Exchangeable Magnesium

The effect of Na on dispersion and the soils hydraulic conductivity can be exacerbated by the presence of excessive exchangeable Mg, as shown by Bakker et al. (1973) on the subsoils of the red brown earth (RBE) from Shepparton, Victoria and in the accompanying Fig. 6 for a Vertisol (from Horn, 1983). Although Bakker et *al.* concluded that **Ca/Mg ratios of less than 2 indicates potential physical problems** on the RBE, no similar threshold value was found for the Vertisols.

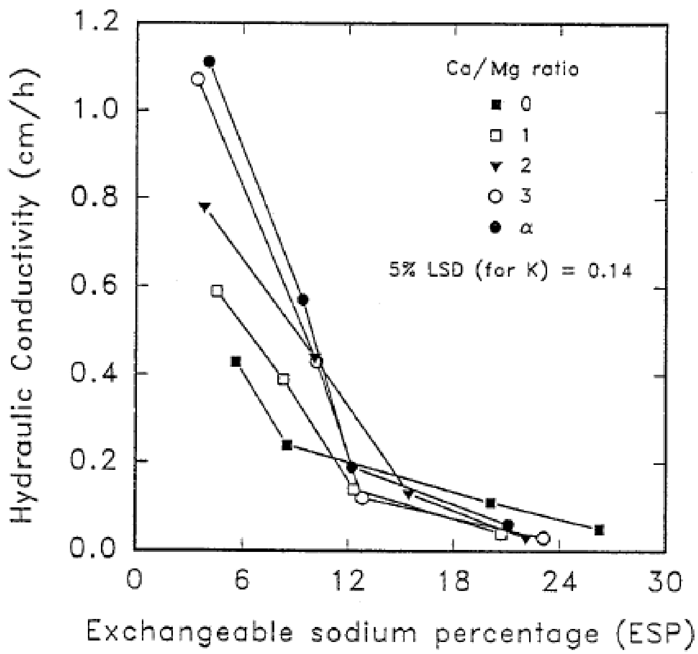
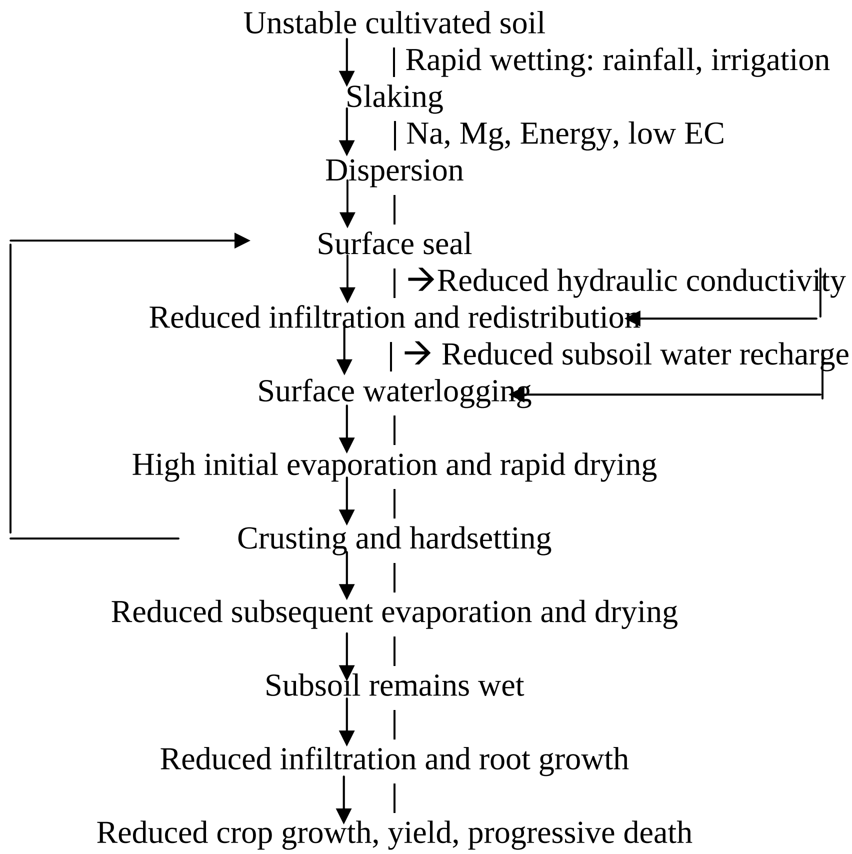


Fig. 6. (from So and Aylmore, 1993). The effect of ESP and Ca/Mg ratios on the hydraulic conductivity of a Vertisol (72% clay) from northern N.S.W. (after Horn 1983).

The following is sourced and modified from Fig. 1 (So and Aylmore, 1993), consisting of a model showing the mechanism of how slaking and dispersion may affect soil physical properties and eventually crop yield (adapted from So 1987).



Clay Type, Silt Content, and Permeability

The type of clay significantly modifies the effect of electrolyte concentration, solution composition, and texture on infiltration/permeability. Expanding clays such as **smectite and vermiculite tend to swell and/or disperse upon wetting and thus decrease the size of pores available for water movement.** Both Waldron et al. (1970), and Christensen and Ferguson (1966) have shown that **expanding clays are especially sensitive to the type of exchangeable cations relative to infiltration/ permeability.** Fireman and Bodman (1939) found greater permeability on a clay loam soil containing predominantly kaolinitic clay than on another clay loam containing predominantly montmorillonitic (smectitic) clay. Both soils showed very similar initial permeability values to distilled water. However, as time progressed, **the permeability decreased more rapidly in the soil containing montmorillonitic clay than the soil containing kaolinitic clay.** The decrease in permeability was attributed to the swelling of the montmorillonitic clay. Chaudhari and Somawanshi (2004) studied the effect of total electrolyte concentration (TEC) and sodium adsorption ratio (SAR) of irrigation water on unsaturated hydraulic properties, viz. unsaturated hydraulic conductivity, wetting front advancement and soil-water diffusivity of clay (Typic Haplustert), clay loam (Vertic Haplustept) and silt loam (Lithic Haplorthent) soil. Unsaturated flow through clay, clay loam and silt loam soils showed different patterns of its dependence on water quality parameters and ESP at high (near saturation) and low (in available water range) water contents. Water quality had larger impacts on the unsaturated hydraulic conductivities of the silt loam soil than on the clay and clay loam soils. The effects of TEC and SAR were both large for the silt loam soil whereas the effects of SAR were predominant for the clay and clay loam soils.

Diebold (1954) linked soil permeability to silt content. He reported that permeability rates were significantly higher in soils with less than 40% silt than in soils with greater than 40% silt.

Alfalfa seedling and young plant responses to flooding and inundation

Numerous studies have investigated response and performance of alfalfa seedlings and young plants to short-term inundation and flooding. Teutsch et al. (2000) reported on a study involving alfalfa plantings which were subjected to flooded and unflooded treatments which were imposed 21 to 26 d after seeding. Flooding was maintained for 11 to 18 d, then plots were allowed to drain naturally. Flooding reduced seedling dry weight regardless of P treatment. Flooding in the autumn reduced dry matter yield the next year at two locations.

Numerous other studies were cited by Teutsch et all (200). Waterlogging reduced the growth of alfalfa seedlings (Fick et al., 1988), a direct result of hypoxic conditions in the rhizosphere (Noble and Rogers, 1994). Barta (1980) found that 7 d of flooding reduced both root and shoot dry weight of alfalfa by ~60% in comparison with an unflooded control. Similarly, Thompson and Fick (1981) reported that 20 d of flooding reduced alfalfa root dry weight by 80% and shoot dry weight by 35%. A reduction in the seedling growth rate during establishment can lead to less vigorous stands with a higher incidence of seedling mortality (Sheard et al., 1971).

Sheard et al. (1971) concluded that slow development of forage species during and shortly after establishment makes alfalfa plants more vulnerable to death when environmental stresses are present. It is reasonable to predict that larger, more developed alfalfa seedlings resulting from increased P nutrition may be better able to withstand excess soil-moisture stress during establishment. Rapid seedling growth is especially critical for late summer seedings.

Barta and Schmitthenner, (1986) reported the susceptibility of alfalfa to extended flooding is well known (Cameron, 1973; Erwin, 1966.), as is the fact that some root rot diseases are favored by waterlogged soils. Phytophthora root rot (PRR) of alfalfa *(Medicago sativa* L.) is a widely distributed disease associated with poorly drained or periodically waterlogged soils. The fungus can kill seedlings or it can affect established mature plants, causing much of the taproot to rot and slough off (Marks and Mitchell, 1971). The affected plants are more vulnerable to environmental stress. Because both injury by flooding and damage by *Phytophthora megasperma* Drechs. f. sp. *medicaginis (P. m medicaginis)* to alfalfa require a water-logged soil, these physical and biological responses may be closely associated.

Barta and Schmitthenner (1986) reported that ten-week-old alfalfa plants that were clipped (harvested) were more susceptible to Phytophthora root rot damage and flooding injury than were 3-week-old plants, even though it has been documented that older alfalfa plants are more resistant to *Phytophthora megasperma* medicaginis. Clipping (harvesting) alfalfa may increase Phytophthora root rot damage and flooding injury.

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Appendices – Attached

Report prepared by Steve VanFossen, USDA-NRCS (retired) Soil Scientist, Miles City, MT

Summary of SAR x SC of grab samples collected from Tongue River @ T & Y Diversion; data used to regress SAR as function of Specific Conductance, Tongue River @ T & Y Diversion.

Summary of Specific conductance and calculated SAR for Tongue River @ T & Y Diversion, 2006; calculated from regression of SAR as function of Specific Conductance, USGS station 06307990. 2006 irrigation season: May 1- September 30.

Summary of daily discharge, daily specific conductance, and estimated SAR of Tongue River at T & Y Diversion and Brandenberg Bridge. Data sourced from USGS web page. Reference USGS sites 06307990, 06307830.

Summary of 24-hour precipitation totals, September 2006. Miles City, MT. Data provided by National Weather Service.

Detailed report of results of X-ray diffraction analyses of selected samples collected from subject field. Analyses and reporting completed by Image and Chemical Analysis Laboratory, Montana State University.

Detailed summary of data collected during initial controlled laboratory infiltration/hydraulic conductivity measurements.

Detailed summary of data collected during second controlled laboratory infiltration/hydraulic conductivity measurements.

Description and latitude/longitude coordination of sample sites.

Comprehensive soil inventory and listing/acreage accounting of smectite-dominated soils along Tongue River corridor between Miles City and confluence of Tongue River with Circle L Creek.