Soil & Water MANAGEMENT **MODULE 4**

WATER AND SOLUTE TRANSPORT IN SOILS

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MONTANA STATE UNIVERSITY
EXTENSION SERVICE

Introduction

This is the fourth module within the Soil and Water *(SW)* Management series provided by the Montana State University Extension Service and Rocky Mountain Certified Crop Adviser (CCA) program. Used in conjunction with the Nutrient Management *(NM)* modules, this series is designed to provide useful, applicable information for Extension agents, CCAs, consultants, and producers within Montana and Wyoming on practices used to manage soil and water resources. Realizing there are many other sources of information pertaining to the transport of water and solutes in soils, we have included an appendix at the end of the module listing additional resources and contacts. To enhance the learning objective and provide CCAs with continuing education units (CEUs) in Soil and Water Management, a quiz accompanies this module. Concepts from the Rocky Mountain CCA Soil and Water Management Competency Areas covered in this module include: water and solute movement in soils and water quality.

Objectives

- Recognize the different ways in which water moves through soil
- Understand the effects of management on water movement and solute transport
- List soil and water management practices that reduce solute transport to protect water quality

Background

Most water on earth is in a continuous cycle between water bodies, land and the atmosphere. An important component of this cycle is the cycling of water in soil. The processes by which water enters, moves through and exits soil are essential for sustaining plants and soil organisms, transporting nutrients and recharging surface and ground water supplies. Water moving in soil also impacts the behavior and transport of soil solutes and their effect on water quality. Water transport processes were introduced in *SW 1*, and water quality considerations and regulations were covered in *NM 12*. Soil solutes refer to the dissolved components of an aqueous soil solution, which can include gases, nutrients, minerals and chemical compounds. The objective of this module is to expand on concepts previously and focus on management practices that influence water/solute transport and protect water quality.

SOIL & WATER MANAGEMENT

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A self-study course from the MSU Extension Service Continuing Education Series

CCA 1.5 SW CEU

4481-4 NOV. 2005

Water Movement in Soil

Soil water enters and moves through soil in response to changes in 'potential energy,' or the energy status of water. Water movement is always 'down gradient' in terms of potential energy, meaning water always flows from higher to lower potential energy. Depending on the direction of the potential energy gradient, water flow may be downward, horizontal or upward (Figure 1). Downward flow occurs under the force of gravity and is predominantly in the large (macro) pores of saturated soils, whereas horizontal and upward flows are the result of capillary forces (the attraction of water to soil particles and itself) in the small (micro) pores of unsaturated soils. Other examples of capillary flow are migration of ground water upward into the soil and the movement of water from furrows or ditches out into a field (Figure 2). Capillary flow in soils is affected by texture and pore size (*SW 1*). Fine textured soils have a greater ability to retain water than coarser soils under unsaturated conditions due to a larger percentage of micropores in fine soil.

Infiltration

Infiltration, the process of water entry through the soil surface, plays an important role in the soil water cycle as it controls how much, and at what rate, water will enter soil. In turn, this can affect soil water storage, crop yields, irrigation efficiency and solute entry into the soil profile.

Figure 2. The effects of capillary flow in a furrow irrigation system. Water from the furrow moves out toward the surrounding soil due to less potential energy in the soil than in the furrow. (Photograph compliments of B. McGlynn, Montana State University)

The two main factors affecting infiltration are hydraulic conductivity and infiltration rate. Hydraulic conductivity refers to the ease of water movement through soil, both horizontally and vertically, and it decreases with a decrease in pore size and water content. Infiltration rate, the speed at which water enters the soil, is related to the soil's infiltration capacity; meaning its ability to absorb water. If water is applied at a rate less than the soil's infiltration capacity, all the water will move through the soil and the infiltration rate will be equal to the rate of delivery. Yet, if water

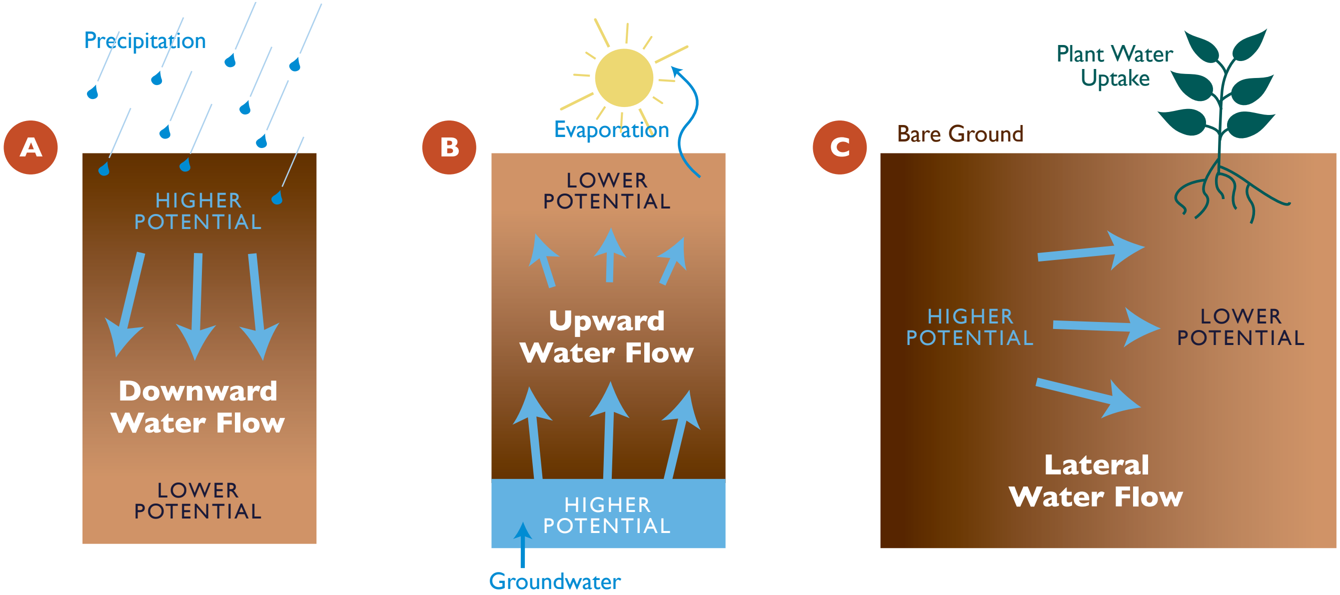

Figure 1. Examples of water flow in soils. Rain falling will saturate the soil surface and percolate downward (A). However, as the rain ceases and water within the macropores has drained, water near the surface evaporates (B) or is taken up by vegetation (C), causing the potential energy at the surface and root zone to be lower than the surrounding soil. Thus, water moves laterally or upward via micropores in response to this gradient.

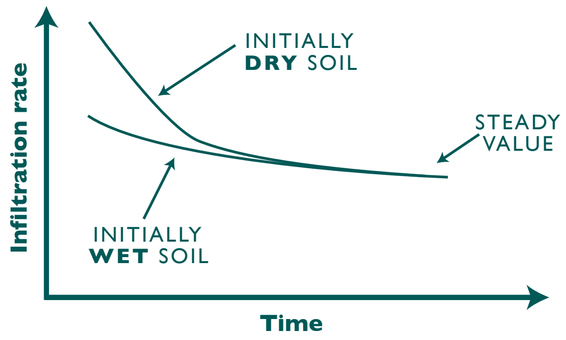

Figure 3. The variation in infiltration rate with different soil water content across time. (Rose, 2004)

delivery is at a rate greater than the soil's infiltration rate, excess water will pond on the surface and run off.

Infiltration rates depend upon a number of factors, including the amount of water applied, initial soil water content, soil properties, hydraulic conductivity and time. Infiltration rates are highest when water initially enters the soil due to water being drawn into soil pores. As pores become water-filled, infiltration rates decrease until a sustainable, steady rate is met (Figure 3). Dry soils generally have higher initial infiltration rates than wet soils due to more available pore space for water to occupy. An exception to this occurs when soils become extremely dry so that they become 'hydrophobic' or water repellent. Hydrophobicity will cause water to bead on the surface of dry, dusty soils rather than infiltrate. Infiltration rates between soil types range from very low to very high due to the variability of soil texture, structure, depth and presence of impeding layers. In general, coarser textured soils have both a higher hydraulic conductivity and infiltration rate than fine textured soils because of connected macropores that can transmit larger quantities of water (Table 1).

Table 1. Typical infiltration rates of different soil textures. (from The Montana Irrigator's Pocket Guide, NCAT, 2003)

Soil Texture	Infiltration Rate (inches/hour)
Very coarse sands	3.75
Coarse sands, fine sands, loamy sands	2.0
Sandy loams, fine sandy loams	1.75
Loams, silt loams, silts	0.75
Sandy clay loams, clay loams, silty clay loams	0.5
Sandy clays, silty clays, clays	0.25

Because of the variability in soil types and conditions, infiltration rates in field soils are likely to have high spatial variability. For example, infiltration through the plow layer may be greater than through the undisturbed subsurface soil. This can result in a buildup of water along the plow line. The same scenario can occur when coarse textured soils overlie fine textured soils. Soil sampling to the depth of each crop's rooting zone can help identify changes in texture, hydraulic conductivity and other soil properties that may affect water and chemical transport through the soil profile.

Preferential Flow

Another example of heterogeneity that exists in almost all field soils and affects water transport is preferential flow. Preferential flow is the movement of free (gravitational) water and any solutes through distinct pathways. These pathways are usually macropores formed by worms, burrowing insects and animals, plant roots, cracks and fissures, or cultivation practices that alter subsoil structure (*SW 1*). Preferential flow affects infiltration rates and solute movement by allowing water to bypass large areas of porous soil. For instance, water percolating through worm holes or cracks will only come in contact with the soil directly surrounding the pathway and can be rapidly transported to the lower portion of the soil profile or ground water (Figure 4). Studies have observed infiltration via preferential flow to be greatest following the first couple of rainfall or irrigation events (Trojan and Linden, 1994; Nachabe et al., 1999), and it is less

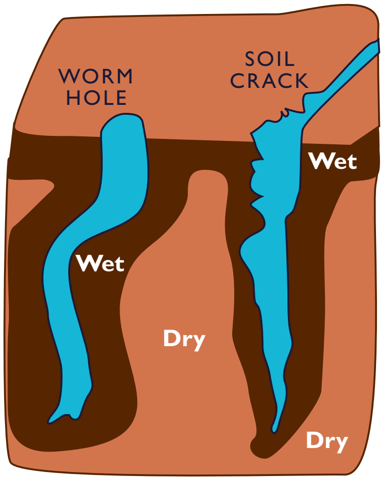

Figure 4. Diagram of preferential flow in a worm hole and crack. (Rose, 2004)

likely to occur under light sprinkler irrigation than flood irrigation. The effect of preferential flow on solute transport will be discussed later.

Ponding and Runoff

Water that does not infiltrate will pond, and, if on a slope, will runoff. Ponding and runoff occur when the infiltration rate is exceeded, surface crusting or an impermeable layer inhibits infiltration, or the soil is at its water holding capacity. Although coarse textured soils typically have higher infiltration rates, they may have less water holding capacity than fine textured soils due to lower total porosity (*SW 1*) and may generate runoff more quickly. Thus, the soil's water holding capacity is an important consideration when determining runoff potential. Runoff on irrigated lands can be minimized by matching application rates with the soil's infiltration rate and water holding capacity while taking steps to prevent surface crusting. Methods to reduce soil crusting and runoff were detailed in *SW 2* and *SW 3*.

Effects of Management on Soil Water Movement

Soil management practices influence soil water movement by altering soil properties and conditions. The effects of these changes on soil water transport are often complex and are highly variable in the field.

Tillage

The effect of tillage management on soil water movement is difficult to predict as both conventional and conservation tillage practices can either increase or decrease infiltration (Christensen et al., 1994). Conventional tillage initially increases porosity and decreases bulk density (the weight of soil within a given volume). These changes may temporarily increase infiltration in tilled soils compared to soils under conservation (e.g., minimum or no-till) tillage systems. However, over time, infiltration may decrease. This change in the tilled soil may be attributed to increased compaction by tillage equipment, disturbance of macropore connectivity and structure, and settling of soil during cycles of wetting and drying (Green et al., 2003). In a study by Ritter (2001), infiltration rates were shown to be higher under reduced till than conventional till in season-long studies. Decreased soil disturbance in conservation tillage systems preserves macropore connectivity and increases aggregate stability. For these reasons, infiltration rates due to preferential flow may be considerably greater in soils under no-till management than in soils that are tilled (Nachabe et al., 1999).

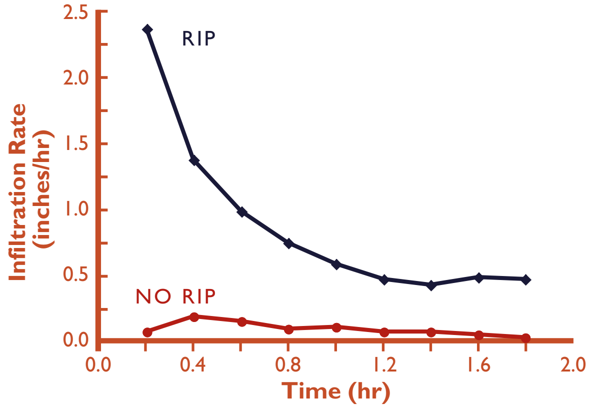

Figure 5. **Water infiltration on rip and no-rip treatments on a Montana sandy loam soil.** Soil was frozen deeper than 3 feet and the depth of ripping was approximately 1 foot. (Adapted from Pikul et al., 1996)

In the northern Great Plains, the infiltration of late winter/early spring thaw water can be inhibited by frozen soils. A study by Pikul et al. (1996) investigated the effect of rip tillage on infiltration into frozen soils. Results showed that when ripping was done after the soil had frozen, infiltration increased approximately 10-fold in the ripped soils compared to the non-ripped soils (Figure 5). Ripping dry soil prior to freezing resulted in no significant change in infiltration because of loose soil flowing into the rip path. Other results of the study found depth of freezing and soil type to influence the degree of increased infiltration following ripping in some sites. Overall, the authors concluded rip tillage combined with residue management for snow catch and surface cover can improve infiltration, soil water storage and grain yield.

Compaction

Compaction by wheel traffic, cultivation equipment, animals or natural processes can affect soil water movement by increasing bulk density and decreasing porosity and infiltration. These changes can result in less soil water storage, poor nutrient movement, slowed gas exchange and restricted root growth, all of which can cause a reduction in crop yields (Cyzt, 2004; Figure 6).

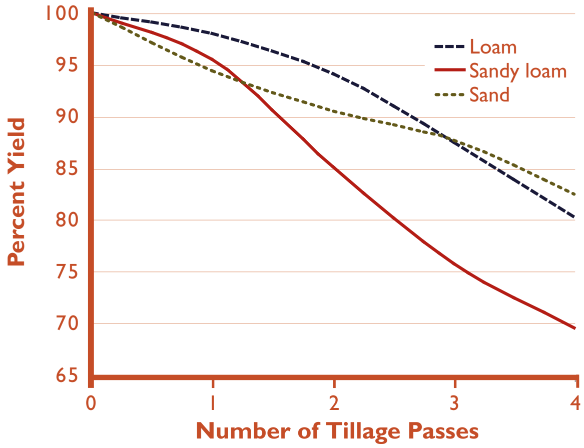

Figure 6. Effect of increasing tillage passes (i.e., increasing compaction) on spring barley yield. Percent yield is percentage of barley yield with zero tillage passes. (Adapted from Cyzt, 2004)

Increased runoff may also occur as a result of compaction (*SW 3*) and with it, off-site pesticide contamination. The degree of soil compaction, and its effect on crop health and yield, depends on the weight and distribution of the load, soil properties, soil water content and landscape position. Surface compaction is primarily caused by tire-soil contact pressure, whereas deep subsurface compaction is caused by heavy axle loads (Jones, 1995). Soil physical properties, including texture, structure, bulk density, SOM levels and water content, control how well soil resists compaction. In general, soils with a mixture of particle sizes, such as loams, are more prone to compaction than soils dominated by one particle size (Jones, 1995). Additionally, soils with low SOM content and poor aggregate stability are more susceptible to compaction forces because they have less structural stability. Moist soil (at field capacity or wetter) is more susceptible to compaction than dry or frozen soil due to its ability to conform to compaction forces (NRCS, 2003). Slight to moderate compaction is generally not a problem until it starts impeding plant growth. Symptoms of soil compaction are shown in Table 2.

Table 2. Symptoms of compacted soils. (Adapted from Jones et al., 1997)

Dark streaks on soil surface where water has remained
Decreased infiltration resulting in excessive ponding and/or runoff
Difficulty in cultivating soil with machinery (more resistance)
Difficulty penetrating soil with a firm wire or welding rod
Discolored plants due to nutrient and water deficiencies (*NM 9*)
Lateral root growth with little or no vertical root penetration into compacted layers; stunted root development
Poor germination and crop emergence
Platy, blocky, dense or massive layers
Reduced yields
Stunted, uneven plant stands

Compaction problems can be diagnosed by observing plant roots' growth patterns, testing bulk density or using a cone penetrometer or soil probe. If roots are shallow and growing horizontally, compaction just below the surface is a likely problem. Measuring bulk density can help indicate changes in compaction over time; increasing bulk density indicates increasing compaction. Another method for assessing compaction is to use a cone penetrometer, a tool that measures the amount of force required to penetrate the soil in pounds per square inch (psi) or bars (1 bar ≈15 psi) (Figures 7a and 7b). A penetrometer reading of 300 psi or greater generally indicates a compaction problem that is adversely affecting root penetration and plant growth; however, this critical value will vary with soil type and moisture content. For instance, some plant growth has been shown to be inhibited at 145 psi (NRCS, 2003).

Compaction by machinery can be prevented by staying off wet soil, reducing tillage and other equipment use, planning traffic patterns and using special equipment to minimize compaction. Over 80% of surface compaction problems occur the first time that wet soil is worked or driven over (Jones, 1995). A quick field test for measuring whether a soil is too wet is to squeeze a small sample of soil; if the soil forms a ball upon release, the soil is probably too wet to work. Reducing tillage by adopting a conservation tillage system will help maintain soil structure, possibly increase SOM content and reduce heavy equipment passes. Establishing designated traffic paths and standardizing wheel track spacing between different machinery will localize compaction to specific areas, and prevent it from occurring over the entire field. Flotation tires, dual tires, low pressure tires and large diameter tires can prevent surface compaction by distributing the weight of the vehicle over a larger distance although subsurface compaction may still occur if axle loads are too heavy.

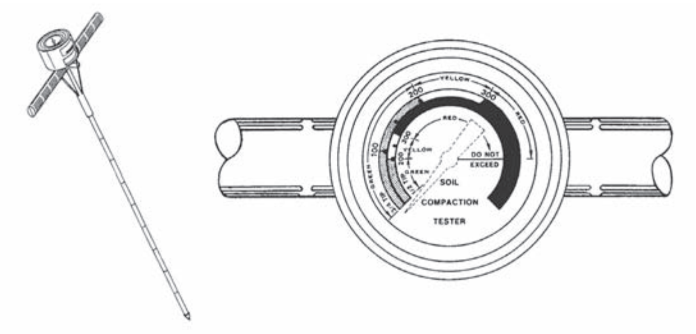

Figure 7a. A penetrometer, or soil compaction tester, has a graded shaft and separate reading scales for each tip size used. (Figure courtesy of D. John, Penn State University)

Figure 7b. A soil probe attached to a rig. (Photograph compliments of R. Mokwa, Montana State University)

Compaction by animals is greatest when the ground is wet; it is fairly minimal when the soil is dry or frozen. Animal induced compaction can be prevented and managed by incorporating good grazing management, such as rotational grazing, into range and pasturelands. Additionally, crop rotations and other residue management practices that increase SOM content may help prevent long-term surface compaction (*NM 15, SW 3*).

To alleviate compaction, tillage practices may be needed to break up surface crusts and plow layers. Shallow compaction can be lessened with chisel plowing at shallow depths. Compaction at deeper depths, however, may require deep tillage or subsoiling. Subsoiling should be done when soil is dry; if the soil is too moist, the compaction problem may actually worsen (Jones, 1995). Fields under years of no-till may experience excessive soil compaction, especially in systems with heavy equipment and random traffic patterns (Magdoff and Weil, 2004). For these situations, tillage may be needed to initially improve the problem (Bauder et al., 1981). Freeze/thaw processes over winter may alleviate compaction to some degree, but should not be wholly relied upon as a treatment method for soils in which compaction is hindering plant growth.

Solute Transport in Soils

Solutes found in soils may include nutrients, pesticides, salts or other naturally occurring or applied chemicals. In the soil environment, many of these solutes are beneficial as they provide plants and soil organisms with food and pest resistance; yet, the movement of solutes off-site to surface and ground water sources can have substantial agronomic, environmental and economic consequences. For example, water sources contaminated by certain nutrients and pesticides can be rendered unsafe for human and animal consumption, and may be toxic to aquatic organisms (*NM 12*). The costs associated with off-site solute movement from an over application of agrichemicals, ineffective treatment of targeted pests (weeds, insects or diseases) or the remediation of contaminated water sources can be quite high (Pimentel et al, 1992). Therefore, understanding how solutes move in soil and learning methods to minimize off-site contamination are important for using chemicals effectively and protecting water quality. Since nutrient transport from agricultural sites to water sources was detailed in *NM 12* and *SW 2* discussed salt movement, this section will primarily focus on the movement of pesticides (e.g., insecticides, herbicides and fungicides) in soil.

Pesticide Fate and Transport

Pesticides are susceptible to a variety of fates once they are applied to plants or to soil (Figure 8). They can be taken up by plants and soil organisms, degraded by chemical and biological processes, retained on soil colloids or lost to the environment via volatilization, runoff or leaching. Pesticide, soil and site properties and management practices affecting each of these fates are discussed below.

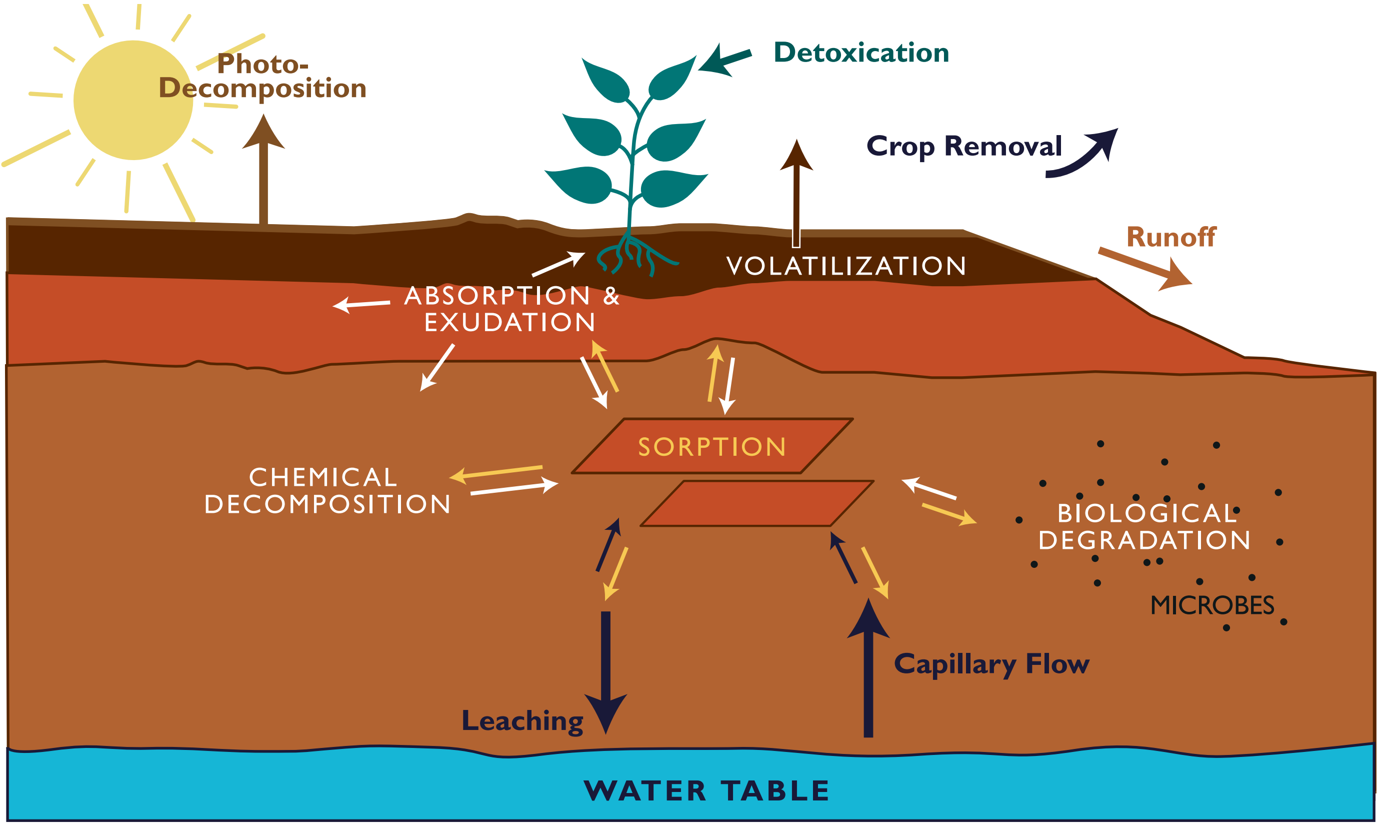

Figure 8. Fate of soil and plant-applied pesticides. (Adapted from Jacobsen and Johnson, 1993)

Pesticide Properties

The two most important agrichemical properties influencing pesticide fate and transport are persistence and mobility. Persistence refers to how well the chemical can resist breakdown. Persistence is measured by half-life, the amount of time it takes for half of the chemical to be degraded or transformed. The majority of pesticides have reported half-lives ranging from a few days to months, although some highly resistant pesticides may demonstrate half-lives exceeding a year. Pesticide half-lives are difficult to predict under field conditions because they depend on numerous factors. These include microbial activity, sunlight (ultra violet light), temperature, soil properties, moisture, application rates and the compound's depth in the soil. In general, conditions that increase microbial activity, such as high temperatures and increased moisture, will result in more rapid microbial degradation (*SW 1*). Increased sunlight also typically increases degradation, while high winds and high evaporation rates can accelerate volatilization (NRC, 1993). Because of these factors, pesticide degradation is much higher at or near the surface than it is deeper in the soil profile.

The mobility of solutes in soil is largely controlled by their water solubility and sorption properties. Chemicals that readily dissolve in water are considered highly soluble and are more easily transported with soil water than less soluble pesticides. Sorption describes how well a chemical 'sorbs', or binds, to soil particles. Similar to many soil nutrients, pesticides have charges that allow them to sorb and be retained on soil particle surfaces (*SW 1*). The ability of a chemical to sorb to soil particles is measured by its sorption partition coefficient, K_D, or by its organic carbon partition coefficient, K_{OC} (Q & A #1). K_D and K_{OC} are the ratio of sorbed chemical to dissolved chemical for soil and organic carbon, respectively. Chemicals with low K_{OC} values (< 300 µg/g) will bind less to SOM and are more susceptible to leaching than chemicals with higher K_{OC} values. However, chemicals with high K_{OC} values may be more susceptible to transport via runoff with sediments that are high in organic carbon content.

Estimated values for water solubility, half-life, and K_{OC} for common pesticides used in Montana and Wyoming are shown in Table 3.The leaching potential of each pesticide is based on these properties. In general,

Q & A #1

What is the difference between K_D and K_{OC}?

Both K_D and K_{OC} are measurements of the ability of pesticides to sorb to soil particles and SOM (organic carbon), respectively. Yet, because K_D is highly dependent on soil types and soil conditions, it is useful to adjust K_D by the percent organic carbon in the soil, thus yielding K_{OC}. Since K_{OC} is less dependent on soil type than K_D, is it often used to represent a pesticide's general adsorption capacity.

pesticides with moderate to long half-lives, low sorption coefficients and high water solubility have a higher leaching potential (Ritter, 2001). Because of the effects of soil biota, SOM, clay content and pH on all of these properties, values are averaged from a number of published sources and should only be used as estimates of the actual value. Please see the appendix for more information on pesticide properties.

Ground water sampling in Montana for pesticides is primarily focused on wells in areas with known or suspected pesticide or nitrate detections. In 2004, 525 well samples were submitted for analysis of between 2 and 23 compounds (Table 4). Most of the detected compounds have relatively low K_{OC} values and long half lives, contributing to their high leaching potential. For example, imazamethabenz methyl ester and one of its breakdown products ('metabolites') were detected 23 and 25 times respectively on the Greensfield Bench near Choteau, Montana. The highest level detected in this area was 10 ppb on June 28, 2001 (Miller 2002); 40 times lower than the 400 ppb health advisory level for imazamethabenz methyl ester. Pesticides in ground water in Montana do not appear to be a problem, nevertheless, it is important to prevent potentially hazardous pesticides from entering water sources. Selecting pesticides with high K_{OC} values and short half lives will help prevent the leaching of pesticides to ground water.

Table 3. Properties of pesticides commonly used in Montana and Wyoming. (WWSA, 1983; Milne, 2004; Worthing and Hance, 1991; Wauchope et al., 1992)

Chemical Name	Water Solubility[‡]	Average Half-life[†]	Soil Sorption Coefficient[‡]	Leaching Potential
	---ppm---	---days---	*K_{OC} ---µg/g---	
2, 4-D amine	796,000	10 (7-21)	20	Medium
Atrazine	33	60-150	100	High
Bromacil	700-815	60-240	32	High
Carbaryl	40-120	10 (7-28)	300	Low
Dicamba	400,000	<14-25	2	High
Diflubenzuron	0.1	7	10,000	Low
Glyphosate	12,000	47 (1-174)	24,000	Low
Malathion	145	1	1,800	Low
Metsulfuron	9,500	30 (14-180)	35	High
Picloram	430	90 (20-300)	16	High
Prometon	620-750	500	150	High
Triclopyr	440	46	20	Very High

*The K_{OC} value represents the sorption coefficient on soil organic carbon.
[†] Half-life values are given at a temperature of 67° F.
[‡] Values for water solubility and K_{OC} are given at pH 7.

Soil Properties

Soil properties that affect pesticide leaching are SOM content, texture, pH, and structure. SOM exists in many different forms and often is a large, physically complex molecule. SOM can have pockets that attract non soluble compounds as well as sites that sorb soluble chemicals preventing leaching. Textural differences in the soil affect sorption of certain chemicals. Chemicals do not readily bind to sandy soils because of the lack of charge on these coarser particles, but they do bind to clay because of clay's overall negative charge and large surface area (*SW 1*). Soil pH alters pesticide behavior by affecting the chemical and biological conditions of soil. In general, lower pH values will reduce leaching and increase degradation (Ritter, 2001). Soil structure affects infiltration and permeability through the profile. Granular or blocky structure increases infiltration and permeability to the deeper root zone, while platy structure will cause an impermeable layer. Pesticides are more apt to leach through a soil with high permeability, whereas low permeability soils may cause the pesticide to be transported in runoff.

Finally, preferential flow conditions, as discussed earlier, can have a significant influence on solute mobility. Pesticide mobility can be greater with preferential flow, because of reduced contact with clays and SOM than by spreading through and around soil particles (Figure 9). Thus, even chemicals with relatively high K_{OC} values can be transported to ground water sources via preferential flow.

Figure 9. Preferential flow of blue dye through a soile profile. (Photograph compliments of M. Weiler, University of British Columbia).

Types of preferential flow channels can have additional influences on flow. For instance, earthworm burrows have a different chemistry than cracks and root channels due to castings lining the channels. These castings are high in organic matter and increase microbial activity which can affect sorption characteristics (Flury, 1996).

Site Conditions

Site conditions impacting pesticide contamination of water bodies include depth to ground water, geologic properties and climate. Areas with shallow ground water are prone to contamination because chemicals have less distance to travel, resulting in less soil to sorb chemicals and less time for degradation (National Research Council, 1993). Changes in geologic material can affect the direction and rate of water and solute movement. For instance, an impermeable layer can cause solutes to flow laterally across the landscape, possibly contaminating shallow ground water or surface water sources. Fractured layers can affect infiltration and preferential flow. The amount of water applied to the soil has a large effect on pesticide leaching and runoff. Regions that receive large amounts of precipitation will generally have more runoff and leaching than arid regions. Plant characteristics, such as transpiration and nutrient and chemical uptake, will also influence pesticide movement.

Table 4. Montana Dept. of Agriculture Ground Water Program: Positive Pesticide Detections for 2004. (Data source: MT Dept. of Agriculture, unpublished data and MT DEQ Circular WQB7, 2004)

Number of Detections	Compound Name	Range of Results ---ppb---	Reporting Limit ---ppb---	MT DEQ Human Health Standards ---ppb---
3	**Atrazine**	0.18 – 0.25	0.03	3
3	Deethyl atrazine **	0.041 – 0.047	0.02	NA
9	Deethyl deisopropyl atrazine **	0.042 – 1.3	0.03	NA
2	Deisopropyl atrazine **	0.067 – 0.076	0.03	NA
2	Hydroxy atrazine **	0.027 – 0.041	0.02	NA
2	Bromacil	2.5 – 3.9	2.5	90
3	Clopyralid	0.7 – 1.1	0.5	3,500
23	**Imazamethabenz methyl ester**	0.20 – 3.9	0.2	400
25	Imazamethabenz methyl acid **	0.20 – 1.5	0.2	NA
1	Prometon	0.45	0.3	100
17	**Tralkoxydim**	0.052	0.05	20
2	Glutaric acid **	0.22	0.05	NA
11	Tralkoxydim acid **	0.19	0.05	NA

** indicates metabolites of the parent compound in bold.

Management Practices that Prevent Solute Contamination

There are a number of practices that minimize agrichemical contamination of surface water and ground water. Point source problems can be eliminated by having a properly designed loading site (thus preventing spills and back-siphoning accidents), by assuring proper storage of chemicals and their disposal, and by maintaining adequate buffer zones around application areas. Preventing non point source problems is more complex and producers need to account for several factors when considering pesticide contamination. As previously discussed, tillage can have multiple effects on infiltration and preferential flow, yet results from a number of field studies assessing the influence of tillage on solute transport vary substantially (Flury, 1996). A study in Saskatchewan, Canada, found leaching to be greater in no-till plots than in tilled plots for eight common herbicides under sprinkler-irrigation (Elliot et al., 2000). These results were credited to greater preferential flow, and thus greater transport, in the no-till plots. However, other studies have found no apparent effect of conservation tillage on pesticide transport (Flury, 1996; Gaynor et al., 1995). Effects of tillage on solute transport may be more pronounced in finer soils than in coarse textured soils (Flury, 1996).

Irrigation practices have a substantial influence on solute transport and its potential to leach or runoff. Table 5 lists general effects of sprinkler and flood irrigation on pesticide leaching potential for different pesticide applications and soil types. Compared to sprinkler systems, flood irrigation systems dissolve solutes more rapidly and are likely to transport them more quickly and deeper in the soil (Flury, 1996; Nachabe et al., 1999).

General conclusions about pesticide transport in irrigated systems cannot be made because of the range of persistence and sorption characteristics (Flury, 1996). For instance, a study by Ghodrati and Jury (1992) found atrazine (K_{OC} = 100 µg/g) to have a higher leaching tendency under continuous ponding than under intermittent ponding in a loamy sand soil, yet the reverse was true for prometryn (K_{OC} = 400 µg/g) and napropamide (K_{OC} = 700 µg/g). Therefore, pesticide properties should always be taken into consideration when selecting pesticide and irrigation application methods.

Finally, the application of needed pesticides should be based on their chemical properties, soil and site conditions, and current irrigation practices. Applications should be timed with consideration to the severity of the pest problem, crop growth cycle and any anticipation of rainfall or irrigation close to application. Pesticide selection should be based on effectiveness on the target organism, toxicity, persistence and solubility. Alternatives to using pesticides include an integrated pest management program, partial treatment and substitutes (e.g., biocontrols; see appendix). Lastly, following all recommendations and precautionary statements listed on the pesticide labels and material safety data sheets (MSDS) will help protect people and the environment.

Table 5. Impact of pesticide and irrigation application methods and soil texture on pesticide leaching potential.

Application Method	Leaching Potential					
	Sprinkler			Flood		
	Clay	Loam	Sand	Clay	Loam	Sand
Surface	Low	Moderate	Moderate	Moderate	Moderate	High
Incorporated	Moderate	Moderate	High	Moderate	High	High
Chemigation	Low	Moderate	High	Moderate	High	High
Foliar	Low	Moderate	Moderate	Low	Low	Low

Summary

Water enters soil via infiltration and moves from higher to lower potential energy. The effect of soil management, such as tillage, on infiltration and preferential flow can vary greatly depending on soil properties, site conditions and time. In general, tillage will improve infiltration in the short-term, whereas conservation tillage systems may result in a long-term increase in infiltration and preferential flow. However, some tillage may be needed in the wheel tracks on soils in years of no-till to correct any compaction. Staying off wet soils, limiting axle loads and practicing good grazing management can prevent compaction.

Understanding the transport of solutes in soil and their potential to contaminate water sources is important for protecting ground and surface water quality. Pesticides with high solubility, long half-lives and low sorption coefficients (K_{OC}) are most susceptible to leaching, especially in soils with high permeability, infiltration and preferential flow. Utilizing management practices such as proper pesticide and irrigation application and timing can help minimize solute leaching and runoff to keep water sources clean.

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Appendix

Books

Soil and Water Quality: An Agenda for Agriculture. 1993. National Research Council, Committee on Long-Range Soil and Water Conservation. National Academy Press. Washington, D.C. 516 p. Approximately $55.

An Introduction to the Environmental Physics of Soil, Water, and Watersheds. C. Rose. 2004. University Press. Cambridge, United Kingdom. 441 p. Approximately $60.

Guides

The Montana Irrigator's Pocket Guide. 2003. National Center for Appropriate Technology (NCAT). Butte, Montana. Available by accessing www.ncat.org or calling 1-800-ASK-NCAT.

Extension Materials

Fate of 2,4-D, Dicamba and Picloram in the Environment. Describes factors that determine what happens to certain herbicides in the atmosphere, water, plants and soils so the herbicides may be used in ways that limit environmental risks. (1997) MT199706AG Free

Subsoiling and Compaction. (1997) MT198328AG Free

Ground Water Contamination Potential Maps of Montana. (1991) MT199107AG Free

Water Quality and Agrichemicals in Montana. (1993) EB 51 Free

Pesticide Management for Water Protection. Discusses pesticide impact on the environment, impact of soil properties and site characteristics on pollution rates, pesticide handling and application, and dealing with spills. Illustrated. (1995) EB 127 Free

Safe Handling of Pesticides—Mixing. The safe handling of open containers of concentrated pesticides requires familiarity with the compound, preparation of the work site, appropriate barriers to limit exposure, and observance of proper procedures for mixing, loading and cleanup and for dealing with spills. (2002) MT200109AG Free

Getting the Most out of Soil-Applied Herbicides. This guide is an overview of factors that influence the fate, effectiveness, and persistence of soil-applied herbicides. (2004) MT200405AG Free

Our Water Resources: Preventing Contamination. This video uses three-dimensional models to show water movement and contamination. (17 minutes, 1989) VIDEO #VI01 $14.95

Montana Farm*A*Syst (Farmstead Assessment System: An Action Program for Safe Drinking Water), (1994) EB 124 $5.00

Nutrient Management Modules (1-15). 4449-(1 to 15). Can be obtained from Extension Publications or on-line in PDF format at www.montana.edu/wwwpb/pubs/mt4449.html. Free

Soil and Water Management Modules (1-3). 4481-(1 to 5). Can be obtained from Extension Publications or on-line in PDF format at www.montana.edu/wwwpb/pubs/4481.html. Free

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Web Resources

http://agr.state.mt.us/pestfert/groundWaterProtection.asp Montana Department of Agriculture Ground Water Protection Program site.

http://wy.water.usgs.gov/projects/pesticide/ Ground-Water Monitoring for Pesticides in Wyoming website from the USGS, Wyoming Department of Agriculture, and Wyoming Department of Environmental Quality.

http://www.deq.state.mt.us/ and http://deq.state.wy.us/ Montana and Wyoming Department of Environmental Quality websites, respectively, with information on laws and regulations pertaining to agrichemicals and water quality.

http://www.arsusda.gov/acsl/services/ppdb/ USDA-ARS Pesticide Properties Database website listing properties of 334 widely used pesticides.

http://www.epa.gov/pesticides/ U.S. EPA Pesticides Program Home Page. Provides resources for pesticide safety, chemical information, pesticide registration, and legislation.

http://www.uwyo.edu/plants/wyopest/factsheets/21-half.pdf Web page about pesticide properties from the University of Wyoming.

http://extoxnet.orst.edu/ 'ExtoNet' website maintained by Oregon State University with information on pesticide properties, labels, and uses.

http://pmep.cce.cornell.edu/facts-slides-self/slide-set/index.html A 'Protecting Ground Water' guide from Cornell University.

http://www.mbmg.mtech.edu/sysearch.htm Miller, K., D. Rise, and C. McDonald. 2002. Ground-water and surface-water quality, herbicide transport, and irrigation practices: Greenfields Bench aquifer, Teton County, Montana. Montana Bureau of Mines and Geology Open-File Report 463.

Acknowledgements

We would like to acknowledge Dr. Bill Inskeep, Montana State University, Dr. Dani Or, University of Connecticut, and Dr. Jon Wraith, Montana State University, as contributing authors for this module; Bridget and David Ashcraft for graphic design and Marla Goodman for final editing.

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