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Irrigation management for groundwater quality protection

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Abstract. Deep percolation flow below agricultural land can transport nitrate and pesticide residues to underlying groundwater. Irrigated agriculture in dry climates can also contaminate groundwater with salt from irrigation water and with trace elements such as selenium leached from the vadose zone. Groundwater contamination by agricultural chemicals can be minimized by using best management practices (BMPs) for crop production (including low-input sustainable agriculture or other source control) and for irrigation. Irrigation systems should be designed and managed for zero or minimum deep percolation during the growing seasons to keep fertilizer and pesticides in the root zone as long as possible. At other times, irrigation efficiencies can be lower to produce enough deep percolation water for leaching salts out of the root zone. Because of spatial variability and preferential flow, however, some deep percolation and movement of chemicals may still occur, even if the irrigation efficiency is 100%. BMPs should be developed to minimize such deep percolation flow.

Introduction

Intensive agriculture is a potential nonpoint source of groundwater contamination. The chemicals of concern are nitrates and pesticides (insecticides, herbicides, fungicides, nematicides, etc.). For irrigated agriculture in dry climates, salts from the irrigation water and trace elements (selenium) leached from the vadose zone can also be a problem. Contamination by anthropogenic chemicals (nitrate and pesticides) is easier to control than salts and trace elements and will be the focus of this paper.

Both surface water and groundwater can be contaminated. In irrigated areas, surface water contamination can be avoided by eliminating tailwater or surface runoff from the irrigated fields. This can be achieved by proper design and management of irrigation systems. Ponding of the water on the lower end of irrigated fields or in designated areas increases infiltration and can aggravate contamination of groundwater.

Nitrates and pesticides are found increasingly in groundwater, and in the U.S. many wells (probably in the tens of thousands) have had to be closed. Human health effects from too much nitrate ingestion include methemoglobi-

nemia in young infants (blue baby disease) and possibly increased stomach cancer in adults (Bouwer 1990; Follet & Walker 1989). Health effects from pesticides may include cancer, nervous disorders, impaired immunity, sterility, and birth defects.

The public reaction is one of fear, anger, frustration, and mistrust of public officials. Treatment options include anion exchange and denitrification (for nitrate) and air stripping, carbon filtration, reverse osmosis, and nanofiltration (for pesticides).

Legislation has been enacted or is in preparation at state and federal levels. Some of this legislation is rather draconian and could have serious impacts on agriculture. Other legislation calls for a better assessment of the situation and for more research, including study of low input agriculture, before remedial action is developed. Maximum contaminant levels (MCLs) generally are the basis for regulatory programs. However, MCLs are difficult to establish and often they are quite uncertain. Acceptable risk is an extremely vague and complicated concept that also involves emotional elements. In the future, farm and irrigation management may have to be aimed increasingly at compliance with environmental regulations. Much can be accomplished with best management practices (BMPs) as a form of source control for fertilizer and pesticide application. BMPs should also be used for irrigation systems to minimize deep percolation flow and resulting leaching of fertilizer and pesticides to groundwater. Legislative developments must strike a balance between public health, environment, and economics. In rich countries, public health and environment may be important factors. In poor countries, where people are starving and food production is the most important issue, productivity and economics may receive priority. For more details regarding the aspects discussed in this introduction, reference is made to Bouwer (1990). The remainder of this paper will address BMPs for farm management and irrigation.

Best management practices

Agronomic practices

Nitrogen

Nitrate contamination of groundwater can be minimized by carefully controlling the timing and the amount of nitrogen fertilizer applications according to crop needs, using slow-release fertilizers and other BMPs to keep nitrate in the root zone as long as possible where it can be taken up by the plant roots or denitrified. This will reduce movement of nitrate to underlying groundwater. Even then, some movement of nitrate to groundwater may be unavoidable. In

cold-to-temperate, rainy climates, most of the nitrate leaching to groundwater occurs during fall and winter. Such leaching can be minimized by planting a fall crop to remove residual nitrogen in the root-zone from the summer season. Farmers tend to base their fertilizer applications on top yields, even though such yields are infrequently realized because of less than optimal rainfall, temperature, and other conditions during the growing season. This practice not only wastes fertilizer, it also increases nitrate pollution of groundwater. Fertilizer applications should be based on realistic yield expectations and on maximizing long-term net profit. Nitrate contamination of groundwater by irrigated agriculture is easier to minimize in dry climates than in humid areas with rain-dependent agriculture.

Pesticides

Pesticide contamination of groundwater can be minimized by using only those pesticides that do not readily leach to underlying groundwater, based on, for example, EPA leaching criteria (U.S. Environmental Protection Agency 1986). Also, pesticides should be kept in the root zone as long as possible because half-lives of pesticides tend to be shorter there than deeper in the vadose zone. The root zone has greater biological activity and more fluctuating water and oxygen levels that may promote faster decay and attenuation.

Applying less pesticide (source control) is another approach. This can be achieved through a broad spectrum of BMPs. BMPs include better timing of applications; introduction of natural enemies or other biological control (integrated pest management); developing and planting more resistant crop varieties with 'built-in' systemic pesticides (maggot-free apples or worm-free tomato plants, for example); early plowdown (cotton) and other agronomic practices; crop rotation; and more effective spraying techniques (in some cases, only about 3% of pesticides applied with present techniques reach their targets). Sometimes, pesticides naturally occurring in plants can be carcinogenic or otherwise toxic (Ames 1989). In Indonesia, introduction of biological control of insects in rice fields has reduced pesticide use by 60% and increased yields by 25% (Agricultural Engineering 1989). Studies in Colorado have shown that basing herbicide applications on the number of weed seeds in soil samples and permitting some weeds to grow in cornfields reduced herbicide applications from 6 kg/ha to 1.5 kg/ha and increased net profits (Schweizer 1989). Also, new pesticides should be developed that are biodegradable, more selective, less toxic to humans, and/or effective at lower applications. Encapsulation of herbicides in starch may be effective to reduce movement to groundwater (Kaniuka 1988). Bacterial strains should be developed that enhance biodegradation of pesticides in the soil.

Irrigation practices

Minimizing leaching or deep percolation flow is a key factor in reducing movement of nitrate and pesticides to groundwater. Theoretically, this is easier to accomplish in dry climates with irrigated agriculture than in areas with wetter climates and rain-dependent agriculture. In these more humid areas, unexpected heavy rains can significantly move nitrate and pesticides to groundwater, especially if the rains occur shortly after the chemicals have been applied. In irrigated agriculture, irrigation systems must be selected, designed, and managed to apply water both uniformly and efficiently. Uniformity is mainly a function of the system itself. Each system will have a characteristic uniformity, i.e., a center pivot sprinkler, a drip system, or sloping border or level basin surface system can each be characterized for uniformity of application. Application efficiency, a term used to relate the targeted water needed to the amount applied, is a function of both the system itself and management.

The main challenges facing the irrigator, once a system has been selected and designed properly, are to determine the optimum timing for an irrigation (*when*), the amount to apply (*how much*), and procedures to use to apply the required amount (*how*). All are management factors that affect the performance (efficiency) of an irrigation system. Some irrigation scheduling techniques are based on soil measurements (water content and tension). Others use weather and climatic data to estimate evapotranspiration rates and to determine when the available water in the root zone is used up. A third category is based on plant measurements, for example canopy temperature as measured with infrared thermometry. This temperature, along with air temperature and relative humidity, is then used to calculate a crop water stress index, which indicates whether the plant has enough water or needs irrigation. Even though much is known about irrigation scheduling techniques, in practice we find that plant appearance, crop harvesting schedules, inflexible water delivery schedules, or historical guidelines are more apt to be used when deciding when to irrigate. More important, Dedrick et al. (1989) found from farmer interviews that definitive soil, plant, or climatic measurements were not used to define *how much* water to apply.

For sprinkler and microirrigation systems in which the water is conveyed to the plant in closed pipes, management is somewhat simpler than with surface irrigation systems. For surface irrigation, which is the predominant type of irrigation world-wide, including the United States (70%, Irrigation Journal 1990), numerous complications exist. Soil infiltration uncertainty (Hanson & Kite 1987), soil textural variability across a field (Jaynes & Hunsaker 1989), and in some instances water runoff from the field being irrigated, all add a level of complexity to surface irrigation management. Even with level basins where no water runs off, Dedrick et al. (1989) found that in practice farmers have

difficulty determining when they have applied the correct amount of water. The difficulties arise from soil textural nonuniformity across a field and its associated infiltration and water-holding-capacity variability, coupled with additional uncertainties caused by fluctuating water delivery flow rates from irrigation district deliveries (Palmer et al. 1989) and flow rates differing from those ordered. All of these variables tend to complicate the irrigation process.

To minimize the movement of chemicals to the groundwater, the uniformity of application and system irrigation efficiencies should be as high as possible. Irrigation systems should be designed and managed so that deep percolation can be near zero during the growing season when fertilizer and pesticides are applied. At other times, the irrigation system can then be operated to produce lower efficiencies so as to leach salts out of the root zone and maintain a salt balance. However, because of spatial variability and preferential flow (see below), 100% irrigation efficiencies do not mean that there is no deep percolation water. Thus, movement of some nitrate and pesticides to groundwater may still occur.

Spatial variability

Soils in irrigated fields are not uniform and can have greatly varying infiltration rates and water-holding capacities from point-to-point (Jaynes & Hunsaker 1989). In addition, the scale of infiltration variability may be on the order of only a few meters. For example, Jaynes et al. (1988a) found that infiltration rates varied by a factor of 15 within a 7- by 9-m area of a sandy loam soil (Fig. 1). This magnitude of variability has profound implications for surface irrigation systems (borders, furrows, and basins). To illustrate the impact of spatially variable infiltration on irrigation uniformity, the infiltration

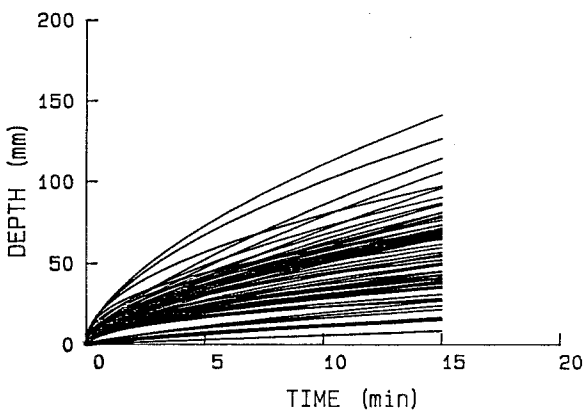

Fig. 1. Accumulated infiltration versus time measured with 63 infiltrometers set at a 1-m spacing on a 7- by 9-m grid in a sandy loam soil (after Jaynes et al. 1988a).

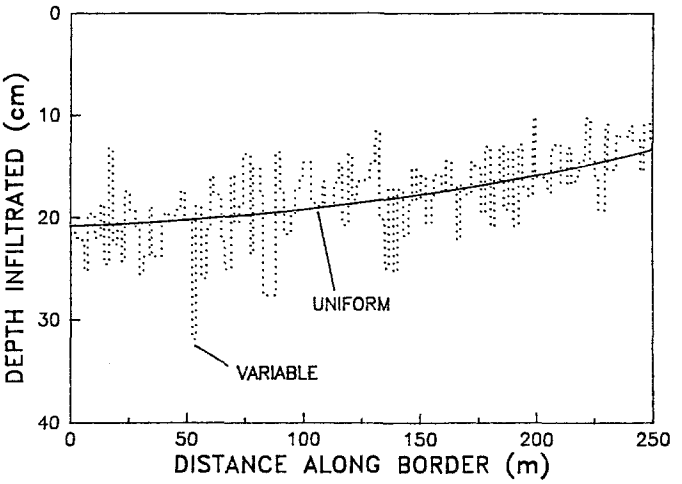

Fig. 2. Results of border irrigation model showing depth of water infiltrated across a level border for spatially variable and uniform infiltration.

parameters measured by Jaynes et al. (1988a) were input into the border irrigation model of Jaynes (1986) for a typical level border. One simulation was run using spatially variable infiltration, and a second was run with uniform infiltration as represented by the mean infiltration parameters found by Jaynes et al. (1988a). Figure 2 shows the distribution of infiltrated water across the border for the two simulations. While on the average, the depth of water infiltrated for both irrigations is the same, spatial variability results in areas that are significantly underirrigated, with no deep percolation but possible yield reduction due to inadequate water, and areas that are overirrigated with perhaps sufficient deep percolation to move agricultural chemicals to groundwater.

As noted earlier, surface irrigation systems are particularly vulnerable to nonuniform water infiltration because infiltration rates are controlled by the soil with all of its nonuniformities. In sprinkler or drip systems, better irrigation uniformity and control of deep percolation water may be possible. However, even though the average irrigation efficiency for such systems, as well as surface irrigation systems, may be very high if uniform infiltration is assumed, there still may be deep percolation water because of spatial variability and preferential flow. Thus, movement of some nitrate and pesticides to groundwater may still occur.

Preferential flow

Preferential flow is the movement of water and solutes through only a limited fraction of the available soil pore space resulting in greatly accelerated movement of water and chemicals. For example, Rice et al. (1986) found that water

and bromide moved as much as 5 times faster through soil than when complete displacement was assumed. Preferential flow can be caused by many factors, including macropores such as cracks, root holes, wormholes, and interpedal voids (Beven & Germann 1982; Dao et al. 1979; Germann & Beven 1985; Hagerman et al. 1989; Kanchanasut et al. 1978; Scotter 1978; Thomas & Phillips 1979; Tyler & Thomas 1977), or instability of flow (Glass et al. 1989a,b; Parlange & Hill 1976; Philip 1975; Raats 1973). Instability of downward flow or 'fingering' can occur in permeable soils that are overlain by much less permeable soils (Samani et al. 1989). Sometimes, preferential flow occurs in soils without obvious macropores (Amoozegar-Fard et al. 1982; Bowman & Rice 1986a,b; Bowman et al. 1987; Jaynes et al. 1988b; Kung 1988). In that case, preferential flow may be caused by microspatial variability. More research is necessary on the factors producing preferential flow and how it can be minimized by irrigation and soil management to minimize transport of agricultural chemicals to underlying groundwater. Prevention of groundwater contamination is better than cleanup and treatment after-the-fact.

Conclusion

Groundwater contamination by agricultural chemicals (nitrate and pesticide residues) from irrigated fields can be minimized by source control (best management practice or BMPs and low input sustainable agriculture or LISA) and by minimizing deep percolation flow during the growing season when the chemicals are applied. Strategies then need to be developed on how to cope with non-uniform distribution of irrigation water in the field, especially as caused by spatial variability and preferential flow.

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