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Controlling Offsite Movement of Agricultural Chemical Residues: Tomatoes

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Introduction

This publication provides growers of processing and fresh market tomatoes with information on farming practices that can help reduce the occurrence of organophosphate and synthetic pyrethroid pesticides in surface water, including streams, lakes, ponds, rivers, and drainage ditches. It describes the current regulatory approach to surface water protection; gives background information on the safe and effective use of pesticides, integrated pest management, and handling runoff water; and demonstrates the self-assessment of the potential risk of offsite movement of an insecticide using flowcharts for specific management practices and field conditions in tomatoes. The risk self-assessment focuses on issues that affect either the number of pesticide applications containing certain active ingredients or the offsite movement of pesticides as drift, attached to sediment, or in water that carries pesticide active ingredients. The publication concludes with research-based management practices that mitigate the risk that pesticide residues will leave the site of application and enter surface water.

More detailed information on implementation of many of these practices is available from sources cited throughout (see the references at the end of the publication). For assistance in determining which practices would be best for your operation or how to implement them, please contact your local UC Cooperative Extension farm advisor.

Why Is This Publication Needed?

The Central Valley occupies about 40% of the land area in California and provides much of the state's agricultural production. Maintaining this productivity resulted in the use of about 119 million pounds of pesticides in 2008 alone (PAN 2008). Water quality in the Central Valley's rivers and streams has been impacted in part due to pesticide movement from agricultural lands. The impaired water bodies recently proposed for listing under the Clean Water Act Section 303(d) include nearly a hundred water body segments in which impairment was due to agriculture. Agriculture is identified as the likely cause of impairment more often than any other pollution source in the state.

Agricultural pesticides reach surface water directly as spray drift or indirectly through irrigation or storm water runoff from treated fields, vineyards, and orchards. Runoff water may transport pesticides in dissolved form or as residues that adhere to soil particles. Among the pollutants often attributed to agriculture is the organophosphate insecticide chlorpyrifos. To indicate the extent of the problem, California agriculture uses 1,349,000 pounds of chlorpyrifos annually, more than any other insecticide (PAN 2008) (chlorpyrifos is not currently registered in California for use in tomatoes). Approximately half of the 303(d)-listed water body segments impaired due to agriculture in the Central Valley are impaired in whole or in part by chlorpyrifos.

The total maximum daily load (TMDL) is a calculation of the maximum amount of a pollutant that a water body can receive and still meet water quality standards. The presence of chlorpyrifos in surface water and its toxicity to aquatic life has been responsible for multiple TMDL projects in California, including one for the San Joaquin River, another for the Sacramento–San Joaquin Delta, and many others in locations where the TMDL definition process is less developed. In one study, chlorpyrifos was responsible for mortality to the test organism *Ceriodaphnia dubia* in seven of ten toxic samples (de Vlaming et al. 2004).

Synthetic pyrethroids are also emerging as a concern. Pyrethroids are a cause for 303(d) listing in about 10% of agriculture-impaired water bodies in California. In a study of toxicity of sediments collected from agricultural waterways, 54 out of 200 sediment samples caused acute toxicity to the test organism *Hyalella azteca*, and pyrethroids were responsible for the toxicity in 61% of those cases (Weston et al. 2009). Chlorpyrifos was the second-most-common contributor to toxicity, responsible for toxicity in 20% of the samples. Recent data also indicate that pyrethroids are present at toxic levels in the water column of irrigation tailwater (runoff at the end of a field) samples. In a study just completed, the pyrethroid lambda-cyhalothrin was responsible for toxicity to *H. azteca* in three out of six toxic samples collected at California agricultural pump stations where tailwater was being returned to nearby rivers; chlorpyrifos was responsible in the remaining three samples (Weston and Lydy 2010). As analyses of environmental samples for pyrethroids become more frequent, it is likely that the water quality effects of pyrethroids will be even more broadly recognized.

The continued use of these effective agricultural pesticides depends on implementing measures to prevent the offsite movement of pesticide residues into surface water. Table 1 gives the active ingredients and trade names for insecticides used in tomato production with reported use over 500 pounds of active ingredient in California during 2008. Organophosphates and pyrethroids represent 43% of this list, with dimethoate, an organophosphate, being the highest-used product based on pounds applied per year.

Current Regulatory Approach to Surface Water Protection

All growers farm under a regulatory requirement not to pollute surface and groundwater. Water leaving agricultural lands as irrigation or storm water runoff can contain pesticide residues, sediment, and nutrients. These discharges in the Central Valley are regulated by California's Central Valley Regional Water Quality Control Board under the Irrigated Lands Regulatory Program. Essentially, the board enforces the California Water Code of 1969 and the federal Clean Water Act of 1972. To this end, the

Table 1. Selected tomato insecticides used in California in 2008 that were registered for use in 2011.

Active Ingredient/common name	Trade name*	Use (lb/yr†)	Chemical class
dimethoate	Dimethoate	48,920	organophosphate
carbaryl	Sevin bait	31,468	carbamate
methoxyfenozide	Intrepid	17,620	diacylhydrazine
diazinon	Diazinon	16,847	organophosphate
bifenthrin	Fanfare and others	14,657	pyrethroid
imidacloprid	various	14,315	neonicotinoid
Bacillus thuringiensis ssp. aizawai	Xentari, Agree	13,153	biological
methomyl	Lannate	12,288	carbamate
Bacillus thuringiensis ssp. kurstaki	Javelin, Dipel	12,070	biological
endosulfan	Thionex	8,274	organochlorine
oxamyl	Vydate	7,234	carbamate
indoxacarb	Avaunt	5,450	oxadiazine
malathion	Malathion	4,865	organophosphate
methamidophos	Monitor	3,393	organophosphate
esfenvalerate	Asana	3,364	pyrethroid
thiamethoxam	Platinum	2,706	neonicotinoid
chlorantraniliprole	Coragen	2,467	anthranilic diamide
lambda-cyhalothrin	Warrior	1,724	pyrethroid
fenpropathrin	Danitol	1,621	pyrethroid
permethrin	Perm-up	1,149	pyrethroid
spinosad	Success, Entrust	1,052	spinosyn
cypermethrin	Mustang, Fury	989	pyrethroid
spinetoram	Radiant	865	spinosyn
dinotefuran	Venom	682	neonicotinoid
pyrethrins	Pyganic	655	pyrethrin
acetamiprid	Assail	597	neonicotinoid
cyfluthrin, beta-cyfluthrin	Baythroid	561	pyrethroid

Source: California Department of Pesticide Regulation.

Notes:

*More than one trade name is used for some active ingredients.

†Pounds per year of active ingredient.

water board has established surface water quality standards in each watershed basin plan and has enforced waste discharge requirements.

The Ag Waiver

In 1982 the Central Valley water board adopted the resolution "Waiving Waste Discharge Requirements for Specific Types of Discharge." The resolution contained 23 categories of waste discharges, including irrigation return flows and storm water runoff from agricultural lands. The resolution also listed the conditions required to comply with the waiver; hence the term "Conditional Ag Waiver." Due to a shortage of resources at the time, the water board did not impose measures to verify compliance with these conditions.

The waiver, set to sunset in 2003, was amended by adopting two conditional waivers for discharges from irrigated lands. One waiver was for coalition groups of individual dischargers to comply with the California Water Code and water board regulations. The second was for growers to comply as individual entities. To be covered by the waivers, the coalition or individual must have filed with the water board by November 1, 2003, a Notice of Intent and General Report that contained specific information about their farm and must have adhered to a plan and timeline that includes, among other things, a surface water monitoring plan.

Water Quality Coalitions

Water quality coalitions are generally formed by growers on a subwatershed basis. A few coalitions were formed for a specific commodity. The San Joaquin County and Delta Water Quality Coalition, for example, encompasses all of San Joaquin County and portions of Contra Costa, Alameda, and Calaveras Counties. The coalition includes about 500,000 acres of irrigated lands and represents 4,500 individual members. The coalition monitors and analyzes the water quality of subwatersheds in surface water and facilitates the implementation of management plans. Coalitions provide outreach and support to growers in response to water quality exceedances at subwatershed monitoring sites in order to enhance the water quality of affected water bodies.

Water Quality Monitoring

The San Joaquin County and Delta Water Quality Coalition currently monitors water quality at numerous sites in large and small subwatersheds in the coalition watershed. Water samples are collected monthly, and sediment samples are collected twice per year. During 2008, the level of a material being monitored exceeded water quality standards many times. At some locations, as many as 40% of the samples exceeded water quality standards for pesticide residues (Karkoski 2008). When more than one exceedance of water quality standards occurs for any contaminant, the coalition must develop a management plan to address it. In addition, any single exceedance of either chlorpyrifos or diazinon triggers the requirement for a management plan.

Water Quality Management Plans

The overall goal of water quality management plans, whether developed by individuals or coalition, is to reduce agricultural impacts on water quality in the plan area. Management plans evaluate the frequency and magnitude of exceedances and prioritize locations for outreach. To achieve the goal of improving water quality, a management plan must include

- identification of the source of constituents that impair water quality
- outreach to growers about irrigation and dormant-season management practices that protect water quality
- evaluation of water quality improvements by monitoring and implementing management practices

Under the management plan landowners or growers must

- help the coalition succeed by participating in efforts to solve water quality impairments identified through water quality monitoring
- stay informed by reading mailings and updates and responding as necessary
- attend grower water quality information meetings
- implement management practices that mitigate the identified water quality concerns

How to Use This Publication

This publication should be used in a two-step process. The first step is to make a risk evaluation of field conditions or operations to identify farming practices that may influence the risk of offsite pesticide movement. This risk evaluation is made using a series of flowcharts. Once avenues of possible pesticide movement from a particular field are identified in the first flowchart, succeeding flowcharts help identify specific conditions and operations that can reduce offsite movement. When followed systematically from beginning to end, the flowcharts guide the user through a step-by-step evaluation of a farming operation to identify potential problem areas. The section "Overview of Risk Evaluation" below describes how to use the flowcharts and contains sample sections of two flowcharts. The complete flowcharts can be found at the end of this publication.

The second step in the process is to understand and implement management practices that address problem areas. These management practices are divided into three broad areas: integrated pest management, water and soil management, and managing runoff water.

Integrated Pest Management

Use integrated pest management (IPM) practices and handle and apply pesticides correctly. IPM is an ecosystem-based strategy that focuses on long-term prevention of pests or their damage through a combination of techniques such as biological control, habitat manipulation, modification of cultural practices, and use of resistant varieties. Pesticides are used only after monitoring indicates that they are needed according to established guidelines, and treatments are made with the goal of removing only the target organism. Coupling IPM techniques with proper pesticide selection, handling, and application can mitigate the offsite movement of pesticide residues. These practices should be the foundation of any water quality protection program. Implementing at least some of them can also reduce risks to human health, beneficial and nontarget organisms, and the environment.

Water and Soil Management

Use soil and water management practices that reduce runoff potential. Runoff occurs when irrigation or rainfall delivers water faster than it can enter the soil. Runoff water can carry dissolved pesticides or transport eroded soil particles that have pesticides adsorbed on them into waterways. To help ensure that irrigation water needs are met and runoff is kept to a minimum, it is important to select the proper irrigation method, system design, and operation. Soil management practices that promote water infiltration and irrigation efficiency include a reduction in tillage, especially when wet, to avoid compaction; increasing soil organic matter; grading the soil slope to accommodate irrigation uniformity; adding soil amendments as needed; and growing cover crops during the off-season to reduce winter rainfall runoff.

Managing Runoff Water

If IPM and water and soil management do not adequately address poor water quality, techniques for physically intercepting, recycling, or chemically treating runoff water can reduce the offsite transport of pesticides in water.

Overview of Risk Evaluation

For a quick overview of the risk evaluation process, we will consider a sample tomato field to illustrate how the flowcharts and management information in this publication can be used to identify and correct the offsite movement of an insecticide. A more detailed discussion of this scenario in the case study presented in the appendix located at the end of this publication. The thick, shaded arrows in the flowcharts indicate the logical progression in considering the most cost effective management practices.

Crop: Tomato, 40 acres, conventional tomato production.

Topography: 0.15% slope.

Soil: Hollenbeck silty clay loam, which tends to crust, limiting the water infiltration rate.

Irrigation system: Furrow irrigation.

Irrigation water: pH 7.5, EC 0.2 dS/m.

Irrigation runoff: About 17% of the applied water.

Drainage: Runoff moves to a drainage ditch at edge of field, then moves to a larger creek.

Pesticide mixing and loading: A pesticide mixing and loading area is located 40 feet from the drainage ditch.

Pest: Potato aphid; 60% of leaves sampled from below the highest flower are infested on July 15, 9 weeks prior to harvest.

Using the Flowcharts

A risk assessment would begin with Flowchart 1, Offsite Movement Risk, which considers possible routes by which pesticide could move off the field and the operations or conditions that may contribute to the movement. The three possible areas of concern are irrigation runoff, spray drift, and storm water runoff.

- **Irrigation runoff risk (fig. 1).** Pesticides applied to the field may be carried in the runoff that occurs during surface irrigation after a pesticide application. The path for this type of risk in Flowchart 1 leads to Flowchart 3.

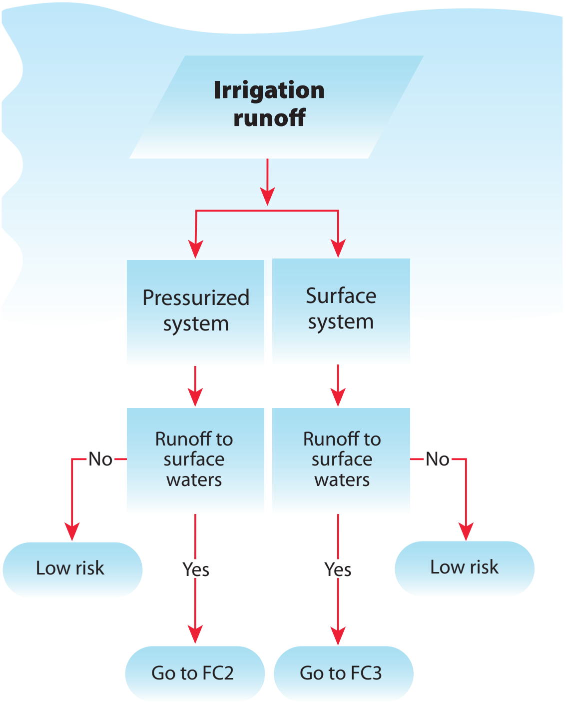

FIgure 1. Excerpt from Flowchart 1, showing path of irrigation runoff risk for sample tomato field.

- **Application near water surfaces (spray drift) risk (fig. 2)**. During spray applications, pesticides may drift into the drainage ditch along the edge of the field. The path for this type of risk leads to Flowchart 5.
- **Stormwater runoff risk (fig. 3).** Pesticides may be carried in storm water runoff in dissolved form and adsorbed to sediments. The risk of transport in runoff is generally low for pesticide applications made during the crop season. However, persistent insecticides can contribute to surface water degradation during storm water runoff after the crop season. The path for this type of risk leads to Flowchart 4.

Management Practices That Reduce Surface Water Pesticide Contamination

Integrated Pest Management

The University of California Integrated Pest Management Program's website, http://ucipm.ucdavis.edu, defines IPM as

> an ecosystem-based strategy that focuses on long-term prevention of pests or their damage through a combination of techniques such as biological control, habitat manipulation, modification of cultural practices, and use of resistant varieties. Pesticides are used only after monitoring indicates they are needed according to established guidelines, and treatments are made with the goal of removing only the target organism. Pest control materials are selected and applied in a manner that minimizes risks to human health, beneficial and non-target organisms, and the environment.

IPM is a systematic approach to pest management. The decision process includes

- selecting varieties that are well adapted to local conditions and have a high degree of pest resistance
- identifying the pest
- understanding pest life cycles and conditions conducive to infestation
- monitoring for the presence, location, and abundance of pests and their natural enemies
- treating when established action thresholds (economic, aesthetic, tolerance) are reached

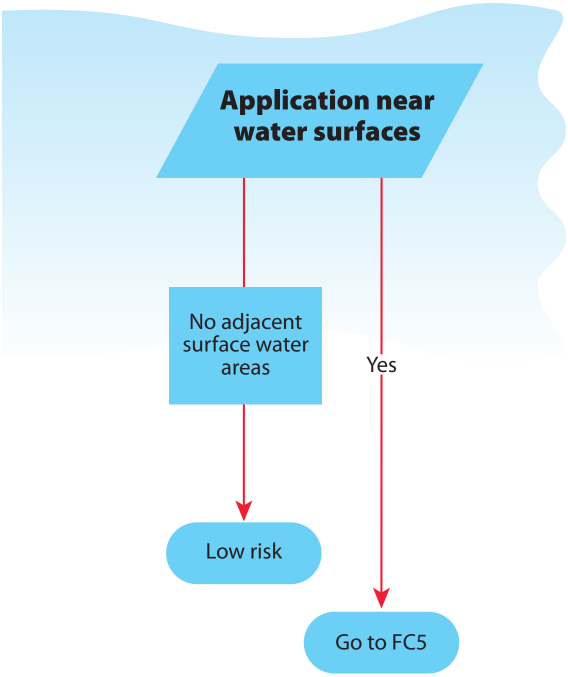

Figure 2. Excerpt from flowchart 1, showing spray drift risk.

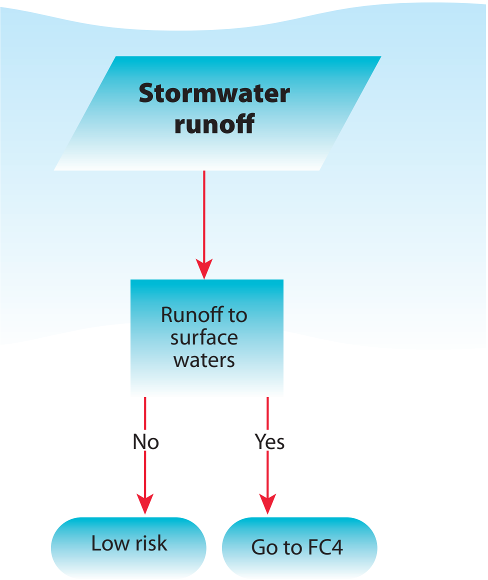

Figure 3. Excerpt from Flowchart 1, showing stormwater runoff risk.

- considering multiple tactics for pest suppression—biological, cultural, and chemical—and selecting the lowest-risk practical and effective approach
- evaluating results

For more information on IPM management actions, see

- UC IPM Pest Management Guidelines for Tomatoes, http://ipm.ucdavis.edu/PMG/
- UC IPM Year Round Program for tomatoes (annual checklist), http://ipm.ucdavis.edu/PMG
- *IPM for Tomatoes*, 4th edition (ANR Publication 3274)
- licensed pest control and crop advisers
- UC IPM advisors and farm advisors

Selecting Pesticides That Reduce Water Quality Risks

Knowledge of how pesticides move and degrade in the environment is useful selecting the best product to use. Pesticides and pesticide residues can move along several different pathways, depending on properties of the pesticide, the application method, and conditions at the application site (fig. 4). This movement is a complex process that, combined with several other factors, influences a pesticide's fate and potential impact on water quality. From the perspective of surface water management, keeping the pesticide on or in the soil by preventing runoff is the most desirable option.

Active ingredients in pesticides used on tomatoes vary in their water solubility, soil adsorption, and half-life. Pesticides with high water solubility can move directly in runoff water, while those adsorbed to soil sediments (which generally have low water solubility) move with the sediment. Half-life is an indication of the pesticide's persistence in the environment, and it is usually measured in the number of days it takes for the pesticide to degrade to one half its original concentration. The soil adsorption coefficient (K_{oc}) can be considered an index of pesticide mobility. The USDA Natural Resources Conservation Service has a model (WIN-PST) that takes these characteristics into consideration in determining a pes-

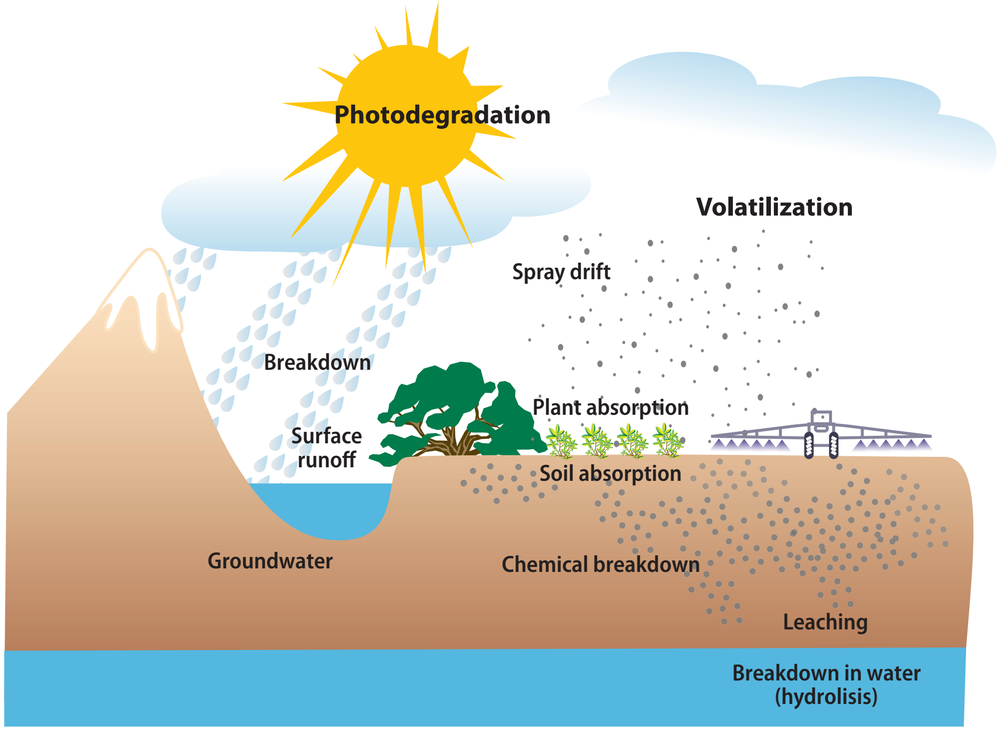

Figure 4. Pesticide fate processes.

Table 2. California-registered tomato insecticides (2011) and their potential to move in solution or as adsorbed particles, with overall pesticide runoff risk.

Active ingredient common name	Trade name	Chemical class	Solution runoff potential[*]	Adsorption runoff potential[†]	Overall runoff risk[‡]
acetamiprid	Assail	neonicotinoid	—	—	—
azadirachtin	Neemix	not classified	—	—	—
bifenthrin	Capture	pyrethroid	low	high	high
buprofezin	Courier	none (chitin biosynthesis inhibitor)	—	—	—
carbaryl	Sevin	carbamate	intermediate	low	moderate
chlorantraniliprole	Coragen	diamide	—	—	—
cyfluthrin	Baythroid	pyrethroid	low	intermediate	high
cypermethrin	Mustang	pyrethroid	low	high	high
diazinon	Diazinon	organophosphate	high	high	very high
dimethoate	Dimethoate	organophosphate	low	low	low
dinotefuran	Venom	neonicotinoid	—	—	—
endosulfan	Thionex	organochlorine	high	high	very high
esfenvalerate	Asana	pyrethroid	low	high	high
fenpropathrin	Danitol	pyrethroid	low	intermediate	moderate
imidacloprid	Admire	neonicotinoid	high	intermediate	low
indoxacarb	Avaunt	not classified	—	—	—
lambda-cyhalothrin	Warrior	pyrethroid	low	intermediate	high
malathion	Malathion	organophosphate	intermediate	low	moderate
methamidophos	Monitor	organophosphate	low	low	low
methomyl	Lannate	carbamate	intermediate	low	moderate
methyoxfenozide	Intrepid	diacylhydrazine	—	—	—
novaluron	Rimon	benzoylurea	—	—	—
oxamyl	Vydate	carbamate	low	low	low
permethrin	Perm-Up	pyrethroid	low	high	high
pymetrozine	Fulfill	not classified (feeding blocker)	—	—	—
pyrethrins	Pyganic	pyrethroid	—	—	—
pyriproxyfen	Knack	pyridine	—	—	—
spinetoram	Radiant	spinosyn	—	—	—
spinosad	Success	spinosyn	intermediate	intermediate	low
spiromesifen	Oberon	keto-enol	—	—	—
tebufenozide	Confirm	diacylhydrazine	high	intermediate	low
thiamethoxam	Platinum	neonicotinoid	—	—	—

Source: Long et al. 2005.

Notes:

[*] Likelihood that the active ingredient will transport from the area of treatment as dissolved chemical in runoff.

[†] Likelihood that the active ingredient will transport from the area of treatment as attachment to soil or sediment particles in runoff.

[‡] Overall likelihood to cause negative impact on surface water quality as a product of the runoff potential and the aquatic toxicity of the pesticide.

— Not available.

ticide's tendency to move in dissolved form with water or to move while adsorbed to sediments. The potential to move offsite, either in solution or with the soil, is categorized as high, intermediate, or low (table 2.)

Aquatic toxicity rankings were extracted from the U.S. EPA ECOTOX database (EPA 2007). The toxicity for EPA indicator species was then used to rank the overall aquatic risk (Long et al. 2005). A pesticide's overall likelihood (risk) to cause a negative impact on surface water quality is a product of the runoff potential and the aquatic toxicity of the pesticide. Table 2 indicates this relationship for commonly used insecticides in tomato production (products without a risk category are new or have not yet been categorized in this system). The table can be used to select pesticides based on the risk of offsite movement to surface water. Changing from one pesticide to another in the same class or in a different class can significantly reduce the environmental risk of offsite movement.

Pesticide Handling Practices That Reduce Water Quality Risks

The risk of offsite pesticide movement is great during mixing and loading due to the possible spillage of undiluted pesticides. Care must be taken to ensure that all of the pesticide goes in the tank. Partially fill the tank with water prior to adding the pesticide to prevent high-strength materials from entering spray lines. Agitation and the use of a bypass can assist good mixing. Avoid overfilling the tank, because spillage can move offsite aided by cleanup water. Mix and load farther than 50 feet from sensitive areas (e.g., open surface water). Use a greater distance if there is a potential for movement in the direction of the sensitive area. Triple-rinse pesticide containers and pour the rinsate into the sprayer tank for use on the field. Also apply tank rinse water to the field. Using a concrete mixing and loading pad with a catchment sump is a good way to reduce risks from mixing and loading near surface water sources.

Pesticide Application Practices That Reduce Offsite Pesticide Movement

Minimizing spray drift

Drift is the physical movement of pesticide droplets or particles through the air from the target site to any off-target site at the time of pesticide application or soon thereafter. All ground and aerial applications produce some drift. How much drift occurs depends on the formulation of the material applied, how the material is applied, the volume used, prevailing weather conditions at the time of application, and the size of the application. Drift can impact surface water quality through direct contact with open ditches or with surface water adjacent to the treated field.

Spray drift can be mitigated by management practices that reduce off-target drift. Application practices that take weather and other site conditions into consideration, have appropriately equipped delivery systems (low-drift nozzles), use appropriate product choice (low vapor pressure and low water solubility), and use buffer zones can significantly reduce the risk of offsite movement of pesticides.

Application conditions

- Do not apply pesticides under dead calm conditions, where drift can easily migrate, or in windy or gusty conditions; do not apply at wind speeds greater than 10 mph (ideally not over 5 mph). Read the label for specific instructions.
- Apply pesticides early in the morning or late in the evening, when the air is usually calmer than during the day.
- Determine the wind direction and take it into account when deciding whether or how to make an application.
- Calibrate and adjust sprayers to accurately direct the spray into the canopy target.
- Delay treatments near ditches and surface water until the wind is blowing away from these and other sensitive areas.
- Do not spray during thermal inversions, when air closest to the ground is warmer than the air above it.

Application equipment

- Use the coarsest spray possible (250 to 400 microns or larger) while still obtaining good coverage and control. Droplet size is one of the most important factors affecting drift: the larger the droplet, the less drift.
- Use low-drift nozzles that produce larger droplets. Fitting a sprayer with air induction nozzles reduces spray drift up to 50% over standard nozzles.
- Use a directed spray on young plants to minimize contact with soil in the furrow.
- Verify that the expected spray pattern is being deposited.
- Service and calibrate spray equipment regularly.
- Check the system for leaks. Small leaks under pressure can produce very fine droplets. Large leaks contaminate soil that can be moved offsite by water.
- Use low pressure and spray volumes appropriate for the canopy size.

Product choice

- Choose an application method and formulation that are less likely to cause drift. After considering the drift potential of a product, formulation, or application method, it may become necessary to use a different product to reduce the chance of drift.
- Use drift control or drift reduction spray additives. These materials are generally thickeners designed to minimize the formation of droplets smaller than 150 microns. They also help produce a more consistent spray pattern and deposition.

- Use spray adjuvants, which can greatly reduce application volumes without compromising pesticide efficacy.
- Use the maximum spray volume per acre and low pressure.

Buffer zones

- Maintain adequate buffer zones around the treated site to ensure that pesticides do not drift onto sensitive areas. A buffer zone is the area between the waterway and where the pesticide is applied. Read the label to determine the size of buffer zone required as related to the active ingredient.
- Treat buffer zones with materials that pose the least risk to aquatic life.
- Change application method. Aerial application has a larger drift potential than ground application. When the risk of drift risk is present, changing to ground application requires a smaller buffer zone.

Avoiding application times prone to risk

Management practices to mitigate offsite movement risk include avoiding application when rain is predicted, especially when the soil is saturated by previous rainfall. Also, pesticides that require application after harvest are at risk of residue runoff when applied to saturated soil or when rainfall is predicted. Apply as near to harvest as possible.

Irrigation Water Management Practices That Reduce Runoff

Any reduction in runoff volume or decrease in the velocity of runoff flow can reduce the amount of both soluble and sediment-attached residues. Managing the irrigation to uniformly apply the correct amount of water to meet crop demand and to increase water infiltration rates can minimize runoff rates and overall runoff volumes.

Irrigation management entails assessing crop water needs and applying irrigation water to supplement stored winter moisture. Irrigation frequency and duration should ensure that enough water infiltrates to meet plant water needs while preventing water loss through runoff and deep percolation. The extent of runoff depends on several factors, including the slope or grade of an area, the texture and moisture content of the soil, the infiltration rate, and the amount and timing of irrigation or rainfall. Runoff that contains pesticides can cause direct injury to nontarget species, harm aquatic organisms in streams and ponds, and lead to groundwater contamination.

Two basic types of irrigation systems are used in tomato production: surface systems (furrow) and pressurized systems (drip). Each has distinct cultural, cost, and offsite movement advantages and disadvantages. Some disadvantages can be overcome using specific management practices.

To prevent runoff in pressurized irrigation systems, water should be applied at a slower rate than it is absorbed by the soil. However, as irrigation progresses, the infiltration rate declines, making runoff more likely. In order to prevent runoff, the system should be turned off before significant runoff occurs. This is especially important in drip systems in the furrow bottom, which in some respects mimics a surface system. Minimizing drip system leaks can also reduce runoff risks. When properly managed, pressurized irrigation systems cause no irrigation water runoff, effectively reducing the risk of pesticide residue moving offsite.

In surface irrigation systems, soil characteristics control the amount of water infiltrated and its distribution across the field as it travels down the slope. Runoff is required to maximize distribution uniformity (how evenly the water is applied across the field). Limiting runoff after a reasonable uniformity has been achieved is a good way to reduce the continued movement of residues offsite. Closed-end furrows used on relatively flat ground can also eliminate runoff, but the successful use of this practice relies on a high infiltration rate and a precise irrigation cutoff. Also, an irrigation system can capture runoff and return it to the irrigation inflow to be applied in subsequent irrigation sets or to another field. At sites with runoff risks, changing from surface irrigation to pressurized irrigation is recommended if possible.

Reducing runoff in surface irrigation systems

Surface irrigation systems (furrow irrigation), while being the simplest irrigation systems with regard to hardware, are the most difficult to manage properly. Control of runoff water is essential for controlling offsite movement of pesticides, sediments, and nutrients.

With furrow irrigation, water is applied to the soil surface, and gravity moves the water across the field. Soil characteristics control both the rate at which water enters the soil and its distribution across the irrigated area. As irrigation begins, the rate at which water enters the soil is high, primarily because of soil dryness and easy access to the soil pores. As irrigation proceeds, the infiltration rate declines rapidly to a sustained rate (also called the basic rate). Figure 5 shows the typical relationship between the amount of water infiltrated into the soil and the duration of irrigation.

A soil's water intake characteristics depend on its physical and chemical composition as well as the chemical composition of the water. Irrigation water with very low salt content or high levels of sodium or bicarbonate can reduce infiltration rates. For more information, see "Reducing Runoff by Improving Water Infiltration," below.

In general, the objective of any irrigation system is to have water infiltrating for the same length of time in all parts of the field. This is difficult to accomplish with furrow systems because it takes time for water to flow from the head of field down the furrow to the tail of the field. This "advance time" causes less water to be infiltrated toward the tail of the field.

For furrow irrigation in tomatoes, more water is almost always infiltrated to the head of the irrigation run than to the tail of the run. The exception is if water is allowed to pond at the end of the row. The part of the field that gets the least water is frequently about two-thirds to three-quarters down the row. Irrigators often increase the water flow rate to the furrow to get water down the row more quickly and improve irrigation uniformity, but this practice increases runoff volume.

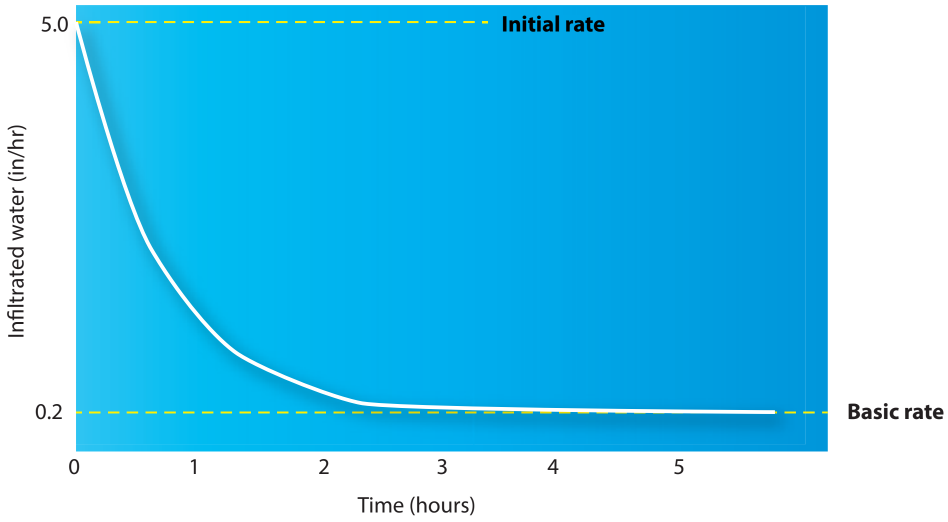

Figure 5. Typical water infiltration characteristics.

In general, keeping the furrows as short as practical helps keep irrigation uniformity high. The tradeoff with short furrows is an increase in labor cost, pipeline cost, and runoff volume. Tailwater return systems can increase the efficiency of furrow irrigation and eliminate discharges.

Measuring applied water in surface systems

One difficulty in managing surface irrigation systems is measuring the volume of water applied to the field. If water is supplied from a pump, a flow meter such as a propeller meter can be installed in the outlet pipe. Follow the manufacturer's recommended installation criteria to obtain accurate measurements. It is difficult to measure water supplied from an open ditch. Consult the irrigation district for help in getting a good estimate of the flow rate to the field.

The following formula may be used to determine the average volume of water applied to a field using a meter that indicates cubic feet per second (cfs):

$$D = Q \times T \div A,$$

where D = depth of applied water (inches), Q = flow rate into the field (cubic feet per second), T = time required to apply water to the field (hours), and A = acres irrigated. If the flow meter reads in gallons per minute (gpm) rather than in cubic feet per second, the conversion is 1 cfs = 449 gpm. For example, assume that flow = 4.45 cfs (2,000 gpm), irrigation duration = 8.6 hours, and area = 8 acres:

$$\begin{aligned} D &= 4.45 \text{ cfs} \times 8.6 \text{ hr} \div 8 \text{ ac} \\ &= 4.8 \text{ inches.} \end{aligned}$$

The depth of water obtained in the above formula should match the amount of water used by the crop since the last irrigation, which is roughly equivalent to evapotranspiration (ET) (see "Irrigation Scheduling to Meet Crop Requirements," below).

Remember that some additional water should be applied because no irrigation system is 100% efficient; furrow irrigation is generally less efficient than pressurized irrigation.

Measuring the distribution of infiltrated water in surface systems is difficult at best. The overall goal is to provide near-equal opportunity time along the length of the furrow.

Reducing runoff in pressurized irrigation systems

Pressurized irrigation includes sprinkler and drip systems. Pressurized systems share the common trait of "designed in" uniformity that overcomes many of the disadvantages of furrow irrigation. Drip irrigation systems allow small amounts of water to be applied slowly and frequently through emitters spaced along polyethylene tubing. The tubing is either buried in the bed or "laid on the surface," usually in the furrow. Runoff is more likely when laid in the furrow; however, good management can minimize or eliminate runoff by reducing irrigation duration, blocking the furrow ends, or capturing runoff in a holding pond or sediment basin.

Irrigation scheduling to meet crop water requirements

Crop water use, or evapotranspiration (ET), is the sum of evaporation from the soil surface and plant water use (transpiration). Climatic factors affecting crop evapotranspiration include solar radiation, temperature, wind, and humidity. Plant and soil factors affecting evapotranspiration include plant type, stage of growth, health of the plant, and soil moisture. The seasonal ET of tomato varies by location in California; in the Central Valley, it ranges from 24 to 27 inches.

Water use begins at a low level after planting in spring when climatic conditions are mild; it increases as the canopy develops and the climatic demand increases, maximizing at around 70 to 80 days after emergence. Water use declines after this period, through leaf senescence and reduced climatic demand.

Estimating water requirements

The best way to determine crop water use is using climatic data and a specific crop's characteristics. Tomato ET can be estimated using the following formula:

$$ET_c = ET_o \times K_c$$

Where ET_c is the crop water use, ET_o is the reference evapotranspiration for a given area, and K_c is a crop coefficient.

Reference ET (ET_o) information is available from a network of nearly 100 California Irrigation Management Information System (CIMIS) weather stations that provide daily reference evapotranspiration values. Two good web-based sources are the UC Statewide Integrated Pest Management website, http:\\www.ipm.ucdavis.edu, and the California Department of Water Resources CIMIS website, http:\\www.cimis.water.ca.gov. Some newspapers and irrigation districts also provide CIMIS ET_o data. The CIMIS program provides real-time (current) values. Historical, or long-term average, ET_o can be more convenient than real-time ET_o information and can be used to prepare an irrigation plan well ahead of the irrigation season. Table 3 gives historical daily ET_o values for three Central Valley locations.

Table 3. Historical (10-year average) reference evapotranspiration ET_o (in/day) for three California Central Valley locations

		Five Points	**Manteca**	**Davis**
Jan	1–15	0.04	0.04	0.03
	16–31	0.05	0.05	0.05
Feb	1–15	0.06	0.07	0.06
	16–28	0.09	0.09	0.09
Mar	1–15	0.11	0.11	0.09
	16–31	0.15	0.14	0.14
Apr	1–15	0.20	0.17	0.18
	16–30	0.22	0.19	0.28
May	1–15	0.23	0.22	0.23
	16–31	0.27	0.23	0.24
Jun	1–15	0.29	0.26	0.28
	16–30	0.30	0.27	0.29
Jul	1–15	0.30	0.27	0.29
	16–31	0.28	0.25	0.27
Aug	1–15	0.28	0.24	0.26
	16–31	0.25	0.22	0.24
Sep	1–15	0.23	0.19	0.21
	16–30	0.20	0.16	0.18
Oct	1–15	0.17	0.13	0.16
	16–31	0.13	0.10	0.12
Nov	1–15	0.10	0.07	0.09
	16–30	0.07	0.05	0.06
Dec	1–15	0.05	0.04	0.05
	16–31	0.03	0.04	0.04

Crop coefficients for tomatoes have been experimentally determined and may be calculated based on canopy coverage. Canopy coverage can be estimated visually or by using digital photography combined with pixel density threshold software at midday. Figure 6 indicates how K_c changes as canopy cover increases. At full canopy, the ET_c would be 110% of ETo. Using historical ET_o averages for your area (e.g., the Manteca CIMIS station from table 3) and the crop coefficient (via the canopy coverage), the weekly crop water use can be determined (table 4). Historical ET_o daily and summed values are available for the Manteca CIMIS stations based on the past 20 years of data at http://ucanr.org/sites/CE_San_Joaquin/Custom_Program/Publications_Available_for_Download/.

Table 4. Weekly tomato water use, April 1 planting, Manteca (CIMIS Station 70), historical ET_o.

Begin date	End date	Canopy coverage (%)	Crop coefficient (Kc)	ETo (in)	ETc (in)
4/1	4/7	0	0.1	1.13	0.14
4/8	4/14	2	0.2	1.25	0.20
4/15	4/21	3	0.2	1.22	0.22
4/22	4/28	4	0.2	1.38	0.27
4/29	5/5	5	0.2	1.53	0.32
5/6	5/12	8	0.3	1.53	0.40
5/13	5/19	15	0.4	1.51	0.55
5/20	5/26	28	0.5	1.65	0.90
5/27	6/2	43	0.7	1.63	1.18
6/3	6/9	59	0.9	1.72	1.50
6/10	6/16	74	1.0	1.86	1.81
6/17	6/23	86	1.0	1.89	1.94
6/24	6/30	96	1.1	1.82	1.94
7/1	7/7	100	1.1	1.93	2.06
7/8	7/14	100	1.1	1.88	2.01
7/15	7/21	100	1.1	1.78	1.91
7/22	7/28	100	1.1	1.73	1.85
7/29	8/4	100	1.1	1.73	1.85
8/5	8/11	100	1.1	1.70	1.82
8/12	8/18	100	1.1	1.64	1.75
Seasonal demand					24.62

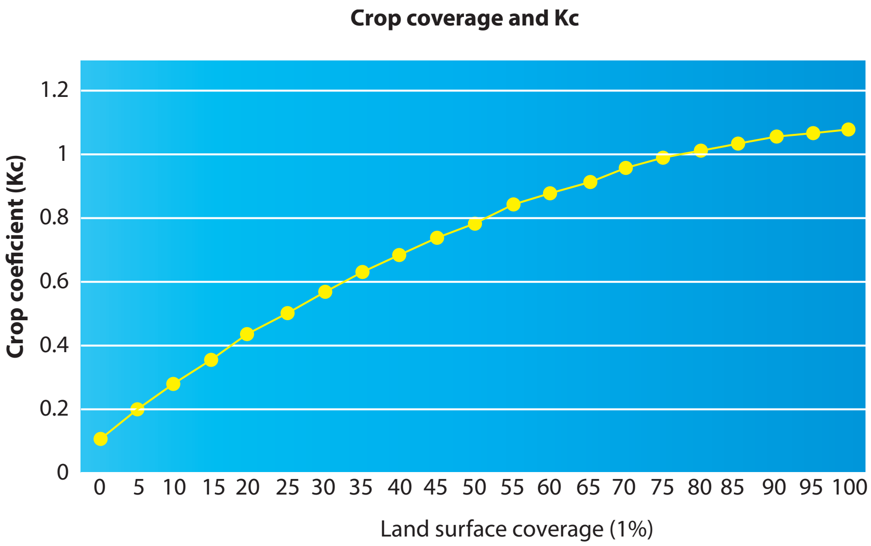

Figure 6. Relationship between crop coverage and crop coefficient.

If rainfall occurs that increases the soil water content (effective rainfall) during these periods, the amount of rainfall must be subtracted from the ET_c, reducing the irrigation requirement. Generally, for rainfall to be effective, it must occur in a quantity that exceeds the daily ET_o by a factor of three. For example, rainfall on April 25 would have to measure 0.6 inch to exceed the 0.2-inch ET_o average for that date. The method used to approximate the effective in-season rainfall in this case is

$$\text{in. of effective rainfall} = \text{in. of rainfall} - 0.6$$

Irrigation frequency: furrow irrigation

With furrow irrigation, the general guidelines are to deplete no more than 45% of available soil moisture in the active root zone before irrigation. A tomato field with a 3-foot root zone would require an irrigation before a depletion of 2.4 inches in a sandy loam, 3.2 inches in loam, and 3.6 inches in a clay loam.

Irrigation frequency: drip irrigation

Under drip irrigation, irrigations should be quite frequent in order to keep the soil water content at a fairly consistent level. While drip irrigation frequency can vary from once a week early in the season to daily in light-textured soils at full canopy, the typical frequency at full canopy is every other day.

Determining the irrigation amount

Once the crop water requirement has been determined, the irrigator must account for losses such as evaporation, runoff, deep percolation, and the lack of irrigation uniformity. These losses depend on the irrigation system type and management. Furrow irrigation can have substantial runoff losses and has larger variability in infiltration than do pressurized systems. This variability in infiltration requires that additional water be applied to deliver a minimum amount of water to all parts of the field. Compared with furrow irrigation, sprinkler systems have greater application uniformity, less deep percolative losses, and little if any runoff. Drip systems have all the advantages of sprinkler systems, along with greater distribution uniformity and less evaporative loss.

To account for these losses and differences between irrigation systems, we calculate the irrigation efficiency to adjust the net irrigation water amount to meet the water requirement of the crop. Irrigation efficiency is the amount of water stored in the root zone and beneficially used by the crop divided by the amount of water applied. To adjust the net irrigation amount for system efficiency and to ensure that even the driest parts of the field receive the net irrigation amount, divide it by the system application efficiency factor (table 5).

Table 5. Estimated application efficiency of irrigation systems

System type	Estimated efficiency (%)
surface irrigation	70–85*
sprinkler	70–80
microirrigation	80–90

Source: Hanson and Schwankl 1995.

Note: *Efficiency reflects the use of a tailwater capture and return system; if such a system is not available, reduce by 15%.

Irrigation amount: Furrow irrigation

For example, to supply 3.6 inches of water to a furrow-irrigated field would require

$$3.6 \div 0.75 = 4.8 \text{ in. of water.}$$

This amount considers that the runoff is recycled using a tailwater recovery system. If such a system is not available, reduce the estimated efficiency of the surface irrigation systems by 15%.

Irrigation amount: Drip irrigation

For example, supplying 2.0 inches of water to a drip-irrigated field at 90% irrigation efficiency would require

$$2 \div 0.90 = 2.2 \text{ in. of water.}$$

Determining the irrigation application time

The irrigation application time, or duration, for a surface irrigation system is determined by dividing the amount of water applied by the flow rate:

$$T = A \times D \div Q,$$

where T = time required to irrigate the field (hours), A = acres irrigated, D = depth of applied water (inches), and Q = flow rate into the field (cfs; 1 cfs = 449 gallons per minute).

Irrigation application time: Furrow irrigation

Using our example of 4.8 inches and a 40-acre field with a water supply of 2,000 gpm, the irrigation time would be

$$T = 40 \times 4.8 \div 4.45 = 43 \text{ hr.}$$

If an 8-acre set were irrigated,

$$T = 8 \times 4.8 \div 4.45 = 8.6 \text{ hr.}$$

Once the irrigation amount and timing of irrigation have been calculated, consider how conditions at the site may affect the application. For example, when using surface irrigation on high infiltration soils, it may be difficult to apply the relatively small amount of water (3.6 inches in our example) due to the large volume required to move water down the furrow and the time required to advance the water to the end of the field: the excess infiltrated water would percolate below the root zone. The selection of appropriate flow volumes and cutoff times discussed below can minimize overapplication of water.

Irrigation application time: Sprinkler and drip irrigation

To determine the irrigation time,

$$T = \mathrm{D} \div \mathrm{AR},$$

where T = time of irrigation (hours), D = depth of applied water (inches), and AR = application rate (inches/hour).

Using our example of 2.2 inches required and an application rate of 0.052 inch per hour, the duration would be

$$T = 2.2 \div 0.052 = 42 \text{ hr.}$$

Deficit irrigation

Once fruit set is complete (roughly when the earliest fruit reach the mature green stage, typically about 4 weeks before harvest), a substantial level of moisture stress can be imposed with minimal loss of productivity. (During fruit set, even moderate levels of soil moisture deficit can substantially reduce fruit set and induce blossom end rot). Deficit irrigation after fruit set may reduce yield by a few tons per acre, but the increase in soluble solids concentration usually results in little or no decline in Brix yield (Hanson et al. 2008). The degree of deficit irrigation possible without loss of Brix yield depends on a number of factors, primarily the soil water-holding capacity and the presence or absence of a shallow water table. Most fields can tolerate irrigation of 40 to 60% of ET_o during the fruit ripening period; fields with high water-holding capacity and good rooting depth may be able to deal with as little as 25% of ET_o over the final 6 weeks.

The ability to precisely control irrigation during fruit ripening depends on the irrigation system used. For drip-irrigated fields, controlling deficit irrigation is easy: simply reduce the hours of run time to deliver the desired percentage of ET_o. In the last 10 to 14 days before the scheduled harvest, drip irrigation can be terminated in most fields without causing severe stress. During deficit irrigation, watch for root intrusion in buried drip systems. If harvest is delayed, make small irrigations to maintain vine health.

With furrow irrigation, it is more difficult to precisely control irrigation volume; consequently, the primary tool for late-season water management has been manipulating the irrigation cutoff date, saving one or more irrigations. Extensive trials in clay loam soils in Fresno County have shown that cutting off furrow irrigation as much as 40 days before harvest has minimal effect on Brix yield, although, as previously stated, fruit yield may suffer a small decline. Even on these forgiving soils, however, earlier cutoff can lead to substantial yield loss. In fields with soil of lower water-holding capacity, cutting off irrigation 40 days before harvest can be too severe a treatment. Using an early cutoff strategy can be risky, particularly if harvest is substantially delayed.

In fields whose water table is within 2 to 3 feet of the surface, deficit irrigation can cause the crop to draw as much as several inches of water from the water table, allowing for a more severe irrigation cutback or an earlier cutoff than would otherwise be appropriate for the field. If the water table is nonsaline, late-season deficit irrigation poses little risk of causing serious decline in yield. However, if the water table is saline, a much larger yield loss is possible with an aggressive irrigation cutback; also, deficit irrigation at the end of the season leaves the root zone with a high EC, increasing next year's water requirement.

Verifying the calculations and applications

The climate-based method described above for determining crop water gives an estimate of demand that should be verified and fine-tuned by soil-based monitoring of actual soil water status. Many devices can monitor soil moisture content and soil tension (see Schwankl and Prichard 2009). If the soil water content decreases or the soil water tension increases over the season, too little irrigation is being applied. If the soil water content increases or the tension decreases after each irrigation, too much water is being applied.

Modifying irrigation systems and management to reduce runoff

As a general rule, the depth of water applied should match the amount of water used by the crop since the last irrigation, which is roughly equivalent to evapotranspiration (ET) (see "Irrigation Scheduling to Meet Crop Requirements," above). Additional water should be applied because no irrigation system is 100% efficient. Furrow irrigation is less efficient than pressurized irrigation.

Modifying irrigation: Surface irrigation systems

Irrigation runoff that enters surface water can carry dissolved and sediment-adsorbed pesticide residues. Soluble residue concentrations in runoff water are fairly consistent for the entire runoff period, so any reduction in the volume of runoff reduces the volume of residues discharged. The degree to which soils erode during irrigation depends on a number of factors, with soil aggregate stability (the ability of soil particles to cling together and resist the forces of flowing water) being the most important. (Aggregate stability can be enhanced by chemical and physical amendments and management practices discussed in the section "Reducing Runoff by Improving Water Infiltration.") Soil erosion rates depend on the soil conditions, including the amount, size, and density of loose particles on the soil surface. For example, erosion increases after cultivation; the degree of soil erosion depends on the velocity of the water and the duration of runoff. Therefore, reducing the peak volume and duration of runoff reduces sediment loss.

The cutoff time is the point at which an irrigation set is ended and no more water is applied to a furrow. Decreasing the cutoff time (shortening the irrigation duration) can reduce the amount of surface runoff from furrow-irrigated fields. The cutoff time for a given field under furrow irrigation depends on the time needed to infiltrate sufficient water along the lower part of the field. This time may need to be determined on a trial-and-error basis. In cracking clay soils, infiltration times of only 2 to 3 hours may be adequate because water flows into the cracks at a very high initial rate, and after the cracks close, infiltration rates become very low. In cracked soils, the cutoff time should occur about 2 to 3 hours after water reaches the end of the field (Hanson and Schwankl 1995). Figure 7 illustrates inflow and outflow rates in a field under furrow irrigation. Note that water must be applied for 700 minutes before it advances to the tail end of the field (before runoff begins), and it must continue to be applied for nearly the same amount of time in order to infiltrate equally at the tail of the field. The result is significant: about two thirds of the water runs off for 500 minutes.

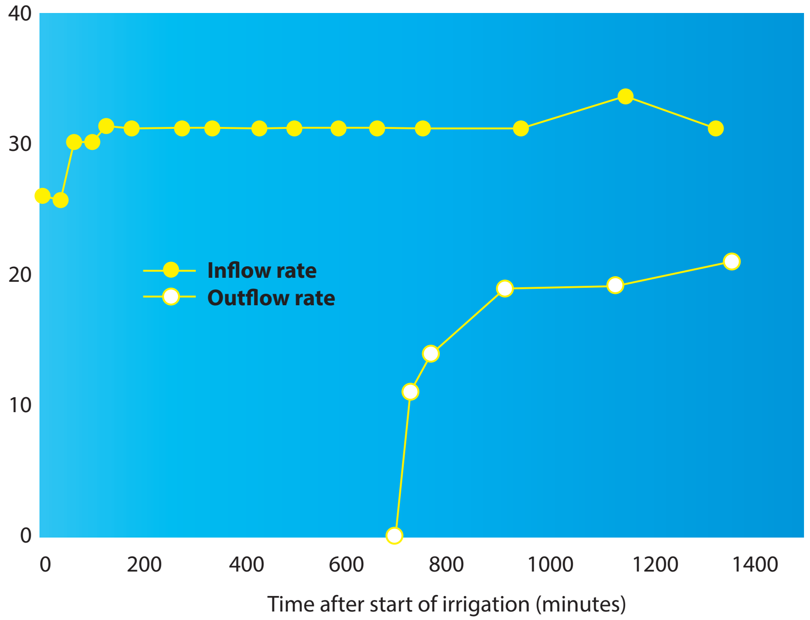

Figure 7. Furrow irrigation inflow and outflow rates (gallons per minute) over the term of irrigation. *After* Hanson and Schwankl 1985.

A shorter cutoff time would reduce runoff volume but may also slightly reduce the distribution uniformity across the field.

Blocking furrows by making small dams in them can increase infiltration and help uniformity. Monitoring each furrow during irrigation is labor intensive, but it can reduce runoff volume.

Converting to pressurized irrigation can reduce runoff, but it requires a significant investment. See "Pressurized Irrigation Systems," below.

Capturing and recycling runoff by using a tailwater collection system can mitigate runoff and reduce the offsite movement of residue, and it can also make irrigation more efficient. For more information see "Tailwater Runoff Collection and Recycling," below.

Modifying irrigation: Pressurized irrigation systems

Pressurized systems should be operated to meet the crop's water requirement while eliminating surface runoff. Uniformity is designed into pressurized irrigation systems, and management should ensure efficiency and the elimination of runoff losses by turning off the system before runoff occurs. When using in-furrow surface drip irrigation in fields with some slope, a small amount of runoff tends to accumulate, potentially causing offsite movement. Unfortunately, most of these highly engineered irrigation systems are not managed to their full potential because they need constant monitoring and maintenance. For example, clogged emitters decrease uniformity, leading to underapplication in some areas and overapplication in others.

Improving Water Infiltration to Reduce Runoff

Poor water infiltration can increase runoff from irrigation or winter rains. Irrigation runoff is typically associated with surface irrigation, but it can occur with pressurized systems on soils with poor infiltration or sloping land.

The first step in determining how to mitigate poor water infiltration is to understand the soil and water factors that influence it. At the onset of irrigation, water infiltrates at a high rate. Initially, the soil is dry and may have cracks through which water can infiltrate rapidly. After the soil near the surface wets for a few hours, the clay particles swell, closing cracks and limiting access to soil pores, which decreases infiltration rates. As wetting continues, the salinity and salt composition of the soil-water (water contained between soil particles) begins to more closely reflect that of the irrigation water, which is generally less saline. This reduction in soil water salinity retards water infiltration.

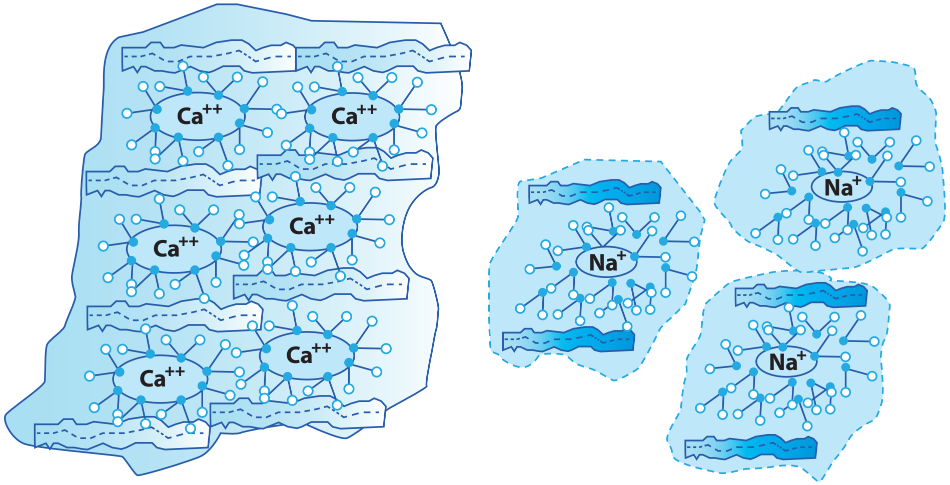

Figure 8. Soil aggregate stability: forming stable aggregates with plentiful calcium on clay exchange sites (left), compared with weak soil aggregates due to low salinity and/or excessive sodium in the soil pore water (right).

Water infiltration can be improved by increasing the soil total pore volume or individual pore size and by providing better access to surface pores. Physical practices that disrupt the soil and applying chemical and organic amendments are attempts to influence these factors. For an in-depth analysis of water infiltration problems and solutions see Singer et al. 1992.

Impact of soil structure on water infiltration

Pores are the spaces between mineral and organic particles in soils through which water and air move. Soils with a predominance of sand (larger, spherical particles) tend to have larger pores, while soils with a predominance of clay (plate-like particles) tend to have smaller pores. With some exceptions, soils with larger pores generally have higher infiltration rates. Water usually moves more slowly through small-pored soils because the smaller pores provide more surface area for water to adhere to. On the other hand, clay soils that form cracks as the soil dries and shrinks can have higher water infiltration rates, at least initially.

Individual soil particles can clump together, forming larger structures called aggregates. The small pores between particles remain, and larger pores formed between the aggregates significantly enhance water infiltration and gas exchange (fig. 8). Soil water salinity and individual mineral constituents, as well as organic matter content, play a significant role in stabilizing soil aggregates and increasing pore size.

Soil crusting

Soil crusts, or surface seals, reduce infiltration by impeding water access to soil pores beneath the crust layer. Crusts form at the soil surface when the soil aggregates become dispersed, causing a loss of porosity. Weak cementation of the crust often follows when the soil dries, slowing water penetration during succeeding irrigations.

Soil surface crusts can be classified as structural or depositional. Structural crusts form when surface soil aggregates are destroyed by the impact of rain or sprinkler droplets. The mechanical breakdown of soil aggregates tends to segregate soil particles, leaving a film of finer particles on top (a sealing layer) that blocks the entry of water into the larger intact pores beneath. Another type of structural crust forms under furrow irrigation through the process of slaking. As the soil is wetted, the mechanical and chemical dispersion of soil aggregates causes the structure to collapse, and the crust becomes hard upon drying. Depositional crusts form when small (usually clay- and silt-sized) soil particles suspended and transported in flowing water settle out of suspension and form a thin, low-porosity surface layer. In agricultural settings, this type of soil crust is most often caused when high-velocity water at the head end of the furrow or check erodes fine particles that settle out when the water slows.

Both structural and depositional crusts are thin and are characterized by higher density, greater strength and smaller pores than the underlying soil. These crusts are usually less than 0.1 inch thick but often limit infiltration for the entire root zone (fig. 9).

In fine-textured silty soils, soil crusts are often caused by excess exchangeable sodium in the soil or irrigation water, or too little total salinity. In coarse- to medium-textured nonsaline and nonsodic soils, continued cultivation can reduce pore size and number to the point where water infiltration is reduced. This problem can be made worse if the irrigation water has very low salinity, such as water from irrigation districts on the east side of the San Joaquin Valley. Additionally, wells that contain a high level of bicarbonate and a relatively low level of calcium encourage crusting.

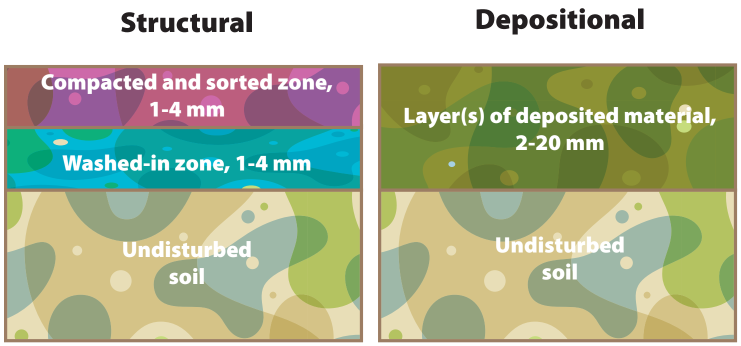

Figure 9. Structural versus depositional crusts.

Irrigation water quality

Irrigation water quality (salinity and sodicity) influences water infiltration rates by affecting whether soil particles tend to absorb water, stay together, or become separated by swelling. The swelling of soil particles causes aggregate breakdown and soil particle dispersion, resulting in the formation of surface crust.

Salinity

The higher the salinity of the irrigation water, the more likely that aggregates will remain stable, preserving infiltration rates. Salinity is measured by determining the electrical conductivity (EC) of the irrigation water (EC_w) or soil water extracted from a saturated soil paste (ECe).

Sodicity

The index for sodicity is the sodium adsorption ratio (SAR), which depends on the relative amounts of sodium, calcium, and magnesium in the irrigation water. The SAR of a soil sample can also be used to estimate exchangeable sodium levels in the soil. With increasing levels of exchangeable sodium, the affinity of soil particles for water increases and aggregate stability decreases, reducing water infiltration rates.

Combined effect of salinity and sodicity

Since both the salinity and sodicity of irrigation water affect aggregate stability and water infiltration, both must be assessed when diagnosing poor infiltration. In the top 3 inches of soil, the salinity and sodicity of the irrigation water and soil are closely linked. Consequently, samples of surface soil and irrigation water must be tested to diagnose the problem and evaluate the likelihood of success of mediation practices. In general, aggregate stability and infiltration rates increase as EC increases and the SAR decreases (table 6). As a general guideline, the SAR should be less than 5 times the EC (fig. 10). The exception is low-salt water with EC values of less than 0.5 dS/m, which is corrosive and depletes surface soils of readily soluble minerals and all soluble salts. It often has a strong tendency to dissolve all sources of calcium rapidly from surface soils. The soils then break down, disperse, and seal, resulting in poor water infiltration.

Table 6. Potential for a water infiltration problem

SAR*	Problem likely, EC_e† or EC_w‡ (dS/m)	Problem unlikely, EC_e or EC_w (dS/m)
0.0–3.0	< 0.3	> 0.7
3.1–6.0	< 0.4	> 1.0
6.1–12.0	< 0.5	> 2.0

Source: Ayers and Westcot 1985.

Notes:

*Sodium adsorption ratio.

†Electrical conductivity of soil extract (soil is saturated paste soil salinity).

‡Electrical conductivity of water (irrigation water salinity).

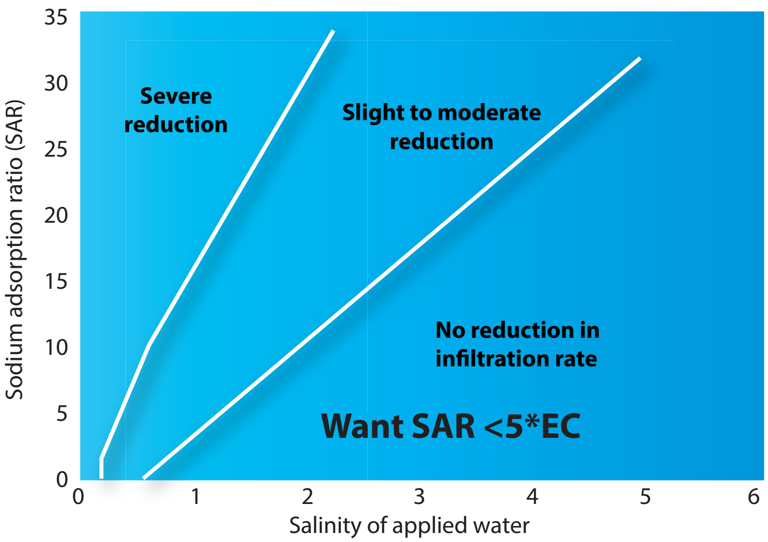

Figure 10. Interaction of total salinity as EC_w with the sodium adsorption ratio (SAR) of irrigation water for causing potential infiltration problems. *Source:* Ayers and Westcott 1985.

The guidelines based on EC and SAR discussed above may not work for all California soils. Some soils contain a large amount of serpentine clays rich in magnesium (Mg) and low in calcium (Ca). In these soils, magnesium may have the same soil-dispersing effect as sodium. Soils with a predominance of montmorillonite and illite clays are also easily dispersed by excess magnesium. Although the diagnostic criteria for such conditions have not been extensively tested, some studies suggest that when the magnesium to calcium ratio of these soils exceeds 1:1, they may be prone to poor water infiltration. Some studies report that high levels of soil potassium can also promote aggregate dispersion and soil crusting.

High levels of carbonate (CO_3^-) and bicarbonate (HCO_3^-) in water increase the sodium hazard of the water to a level greater than that indicated by the SAR. In alkaline soils, high levels of carbonate and bicarbonate tend to precipitate calcium carbonate (lime, $CaCO_3$) and magnesium carbonate ($MgCO_3$) when the soil solution becomes concentrated during soil drying. The concentrations of calcium and magnesium in the soil solution are reduced relative to sodium, and the SAR of the soil solution tends to increase.

An adjusted SAR value may be calculated for water high in carbonate and bicarbonate if the soil being irrigated contains free lime (calcareous soil). The adjusted SAR and knowledge of soil properties help determine management practices when using high-bicarbonate water.

Mitigating poor water infiltration

Solving poor infiltration by modifying irrigation practices, as discussed in other sections of this publication, should always be the starting point and will generally be less costly than the soil and water modifying treatments discussed below. Poor water infiltration that is not amenable to improvement by optimizing irrigation system design and operation may be mitigated by improved management of soil organic matter or by soil tillage or by using chemical amendments.

Tillage

Shallow tillage can disrupt structural and depositional crusts. Where crusting reduces infiltration rates, a single tillage can restore infiltration rates. However, after the crop has spread into the furrows, tillage may not be an option. Shallow tillage using a sweep or rolling cultivator can effectively break up the surface crust, and shallow tillage to incorporate a pesticide after application can reduce the residues available for offsite movement.

Managing soil organic matter to reduce runoff

Soil organic matter helps stabilize soil aggregates by increasing the number of exchange sites in the soil matrix and encouraging microbial activity. Soil microbes that decompose soil organic matter produce polysaccharides and polyuronides, which act as binders to stabilize aggregates, improving porosity and water infiltration. Over time, continued cultivation reduces the organic matter content and aggregate stability of soils. These changes can reduce water infiltration and increase the runoff potential.

In most of California, it is difficult to increase and sustain soil organic matter under the prevailing warm, semiarid conditions that favor rapid organic matter decomposition. Adding organic matter to improve or sustain aggregate stability and water infiltration must be incremental and continual to be effective. Growers can achieve this in the following ways.

Crop residues. After harvest, residues of field crops that are shredded or incorporated can add organic matter and a certain amount of nutrients to the soil. Crop residue biomass in California's Central Valley ranged from 9,560 pounds per acre for corn after grain harvest to 570 pounds per acre for onions; for tomato, the average was 2,880 pounds per acre. Wheat biomass was 4,800 pounds per acre after grain harvest, but after baling, only 670 pounds remained (Mitchell et al. 1999).

Manure and other organic materials. With proper handing and management to avoid risk of crop contamination by human pathogens, animal manures or compost can help increase soil organic matter content and improve water infiltration. However, the application of manures is currently uncommon due to the limited availability of manures.

Cover crops. Cover crops can help protect the soil surface from droplet impact during winter rainfall and can provide significant organic matter biomass for decomposition and microbial stabilization of soil aggregates. In addition, cover crop residue can slow the velocity of surface water, reducing erosion and subsequent depositional crusting. In one study, a winter cover crop of triticale was planted to bed tops in a tomato field in early November and chemically controlled at a height of about 8 inches in mid-February (Miyao et al. 2004). The result was a 40% reduction in storm water runoff volume and a 70% reduction in runoff turbidity compared with a field with no cover crop. Less expensive options include using barley or oats.

Chemical amendments. Adding chemical amendments to water or soil can improve water infiltration by increasing the total salt concentration or decreasing the sodium adsorption ratio (SAR) of the soil-water. These actions enhance aggregate stability and reduce soil crusting and pore blockage. Four types of materials are used to ameliorate water infiltration: salts, as fertilizers; calcium materials; acids or acid-forming materials; and soil conditioners, including polymers and surfactants.

Salts. Any fertilizer salt or amendment that contains salts, when applied to the soil surface or dissolved in irrigation water, increases the salinity of the irrigation water and ultimately influences the soil-water. Whether increased salinity is advantageous depends on the SAR of the irrigation water. The largest effect of salt addition is in irrigation water that has very low salinity (EC less than 0.5 dS/m). Increasing salinity to an EC above 4 dS/m has little effect on infiltration.

Calcium materials. Adding calcium salts to soil and water increases the total salinity and soluble calcium. The calcium salt commonly used on alkaline (high-pH) soils is gypsum ($CaSO_4$), but calcium chloride ($CaCl_2$) and calcium nitrate ($CaNO_3$) are sometimes used. These are fairly soluble and can easily be applied though the irrigation water. Care should be taken if the water contains more than 2 meq/L of bicarbonate (HCO_3). Adding gypsum to such water through a drip system significantly increases the likelihood that lime precipitate will clog the system; if it does, application of acid to decrease bicarbonate concentrations may be necessary. Lime and dolomite are used only for broadcast applications on acid soil, as they are virtually insoluble under alkaline conditions.

Adding gypsum to irrigation water at rates that supply 1.0 to 3.0 meq/L of calcium is considered low to moderate; rates that supply 3.0 to 6.0 meq/L of calcium are considered moderate to high. The following sample calculations show how to estimate the quantity of gypsum required to improve infiltration. Table 7 lists the amount of gypsum and other products needed to increase the calcium content of irrigation water by 1 meq/L per acre-foot; applying 234 pounds of 100% pure gypsum per acre-foot of water provides 1 meq/L of free calcium. It is rarely necessary to inject gypsum constantly. Injection every other or every third irrigation may be all that is necessary to end the season with the required amount. Injecting gypsum in drip irrigation during the season is usually more beneficial than applying it to the surface during the fallow season.

Table 7. Amount of amendments required for calcareous soils in order to increase the calcium content in the irrigation water by 1 meq/L

Chemical name	**Trade or chemical name and composition**	**Amount of amendment required to obtain 1 meq/L free Ca[*] (lb/ac-ft of water)**
ammonium polysulfide	Nitro-sul, 20% N	69[†]
	Nitro-sul, 40% S	136[‡]
ammonium thiosulfate	Thio-sul, 12% N	110[†]
	Thio-sul, 26% S	336[‡]
calcium chloride	Electro-Cal, 13% Ca	418
calcium polysulfide	Lime-sulfur, 23.3% S	191
gypsum	$CaSO_4$ · 2H2O, 100%	234
monocarbamide dihydrogen sulfate/sulfuric acid	N-phuric or US-10, 10% N	148[†]
	N-phuric or US-10, 18% S	242[‡]
potassium thiosulfate	KTS, 25% K2O, 26% S	256
sulfur	S, 100%	43.6
sulfuric acid	H2SO4, 100%	133

Notes:

[*] Salts bound to the soil are replaced on an equal ionic charge basis and not on an equal weight basis.

[†] Combined acidification potential from S and oxidation of N source to NO_3 to release free Ca from soil lime. Requires moist, biologically active soil.

[‡] Acidification potential from oxidation of N source to NO_3 only.

An alternative to treating water with calcium materials is broadcasting amendments such as gypsum on the soil surface prior to planting. The primary advantage of this approach is that it is often less expensive than treating water. Surface applications are most effective when gypsum is applied at rates equivalent to 1 to 2 tons per acre prior to planting. When applied in the fall, higher rates must be used.

Acids and acid-forming materials. Commonly applied acid or acid-forming amendments include sulfuric acid (H_2SO_4) products, soil sulfur, ammonium polysulfide, and calcium polysulfide. The acid from these materials dissolves soil-lime to form a calcium salt (gypsum), which dissolves in the irrigation water to provide exchangeable calcium. The acid materials react with soil-lime the instant they come in contact with the soil. Materials containing elemental sulfur or sulfides must undergo microbial degradation in order to produce acid. This process may take months or years, depending on the material and particle size (in the case of elemental sulfur). Since these materials form an acid via the soil reaction, they reduce soil pH if applied at sufficiently high rates.

Acids are applied to water for two purposes in relation to water infiltration problems. The first is to dissolve soil lime (the soil must contain lime if acids are used), which increases free calcium in the soil-water and improves infiltration. The second is to prevent lime clogging in drip systems when adding gypsum to water containing greater than 2 meq/L bicarbonate.

Table 7 indicates that it takes 133 pounds of 100% pure sulfuric acid per acre-foot of water to release 1 meq/L of calcium. This assumes that the acid contacts lime in the soil, neutralizing the carbonate molecule and releasing calcium. This is the same amount of acid required to neutralize 1 meq/L of bicarbonate in the water. If the water contains bicarbonate, the acid will neutralize it, converting it to carbon dioxide, which is released to the atmosphere. To dissolve lime in the soil, the level of acid applied must be greater than the level of bicarbonate in the water; if the level of acid is lower, the pH of the water will not decrease.

Soil conditioners. These primary soil condition amendments are organic polymers and surfactants. Although there is a long history of developing and testing other amendments, such as synthetic and natural soil enzymes and microbial soups, not enough data exists on them to conclude that they are uniformly effective. Surfactants, or wetting agents, reduce the surface tension of water; they are not effective in agricultural soils.

Organic polymers, mainly water-soluble polyacrylamides (PAM) and polysaccharides, stabilize aggregates at the soil surface. These extremely long-chain molecules wrap around and through soil particles to bind aggregates together. This action helps resist the disruptive forces of droplet impact and also helps decrease soil erosion and sediment load in furrow irrigation systems. Studies have shown that PAM can improve infiltration into soils with illite and kaolinitic clays common in the northwest United States (Sojka et al. 2007). The studies were conducted on erosive soils with low aggregate stability on slopes that result in sediment transport and deposition. Under these conditions, PAM tended to increase infiltration by maintaining the integrity of aggregates and by preventing soil erosion and the formation of a depositional surface seal. Research conducted in California found that infiltration is not improved in soils with the mostly montmorillonite (swelling) clays typical of the San Joaquin Valley (Long et al. 2010a). The use of PAM on sandy soils in California reduced the infiltration rate up to 50% (Ajwa and Trout 2006). For more information on water-soluble PAM, see the section “Treatment of Runoff Water” later in this publication. Water-soluble PAM should not be confused with the crystal-like, cross-linked PAMs that expand when exposed to water and do not influence water infiltration. These cross-linked PAMs enhance the water-holding capacity of soils for small-scale applications, such as in container nurseries.

The effect of organic polymers on infiltration depends on polymer properties such as molecular weight, structure, and electrical charge, along with the salinity of the irrigation water. Charged (ionic) and noncharged (nonionic) polymers added to very pure water (surface water where EC is 0.03 to 0.1 dS/m) can behave differently when added to higher-salinity well water (EC above 0.8 dS/m). Polymers have been shown to work best when sprayed on the soil surface at a rate of about 4 pounds per acre, followed by an application of gypsum in soil or water.

Capturing and Filtering Surface Water and Sediments

Reducing the volume or velocity of runoff water can reduce the offsite movement of residues, whether in solution or attached to sediment. The most common methods of capturing and filtering surface water and sediment are sediment basins growing vegetation at the tail of the field or in drainage ditches.

Storing runoff

Storage of runoff water from storm events in impoundments is often suggested as a mitigation practice for preventing offsite movement of chemicals. The sheer volume of runoff makes this a poor option. Storms are rated as to the frequency at which a particular amount of rainfall in a given duration is expected to return, on average. A 2-year, 24-hour storm would be the rainfall event one could expect during a 24-hour period on the average of every 2 years. For example, a 2-year, 24-hour storm in Stockton, California, is 1.6 inches. That amount of rainfall on a 40-acre parcel would produce over 1,700,000 gallons, or 5.3 acre feet, of water, equivalent to a 1-acre pond over 5 feet deep. A single hundred-year storm would require three times that volume. Of course, some of the water would infiltrate into the field. However, if one storm came on the heels of another, most of the rainfall would run off. For more information, see Schwankl et al. 2007a.

Sediment basins

A sediment basin or trap is located at the low elevation portion of the field with a overflow pipe or spillway. These basins can be designed by the Natural Resources Conservation Service (NRCS) or a civil engineer on a site-specific basis and should be installed using proper construction methods (see fig. 11). Basins should be sized to retain the entire runoff volume. If the runoff volume is small, a basin

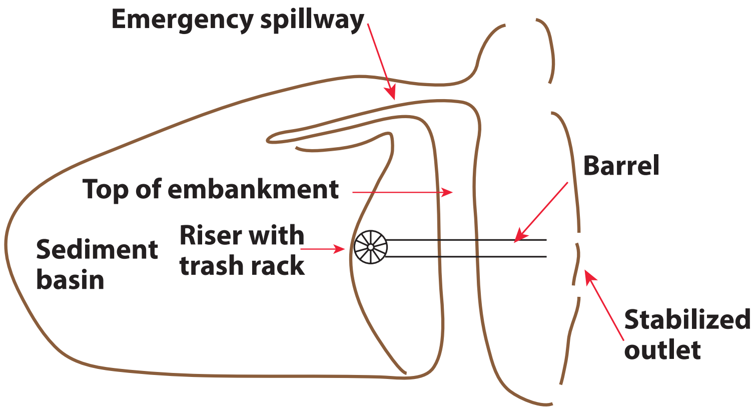

Figure 11. Sediment basin with spillway and release structure.

effectively reduces offsite movement of sediment containing adsorbed pesticide residues. If runoff is high enough to cause low retention times, sediment removal efficiency declines rapidly.

Effectiveness in removing pesticide residues

Long et al. (2010) found that retention times of 60 to 90 minutes in a sediment basin that was 1.4% of the irrigated area effectively removed particles coarser than fine silts. Finer soil particles, which generally adsorb pyrethroid pesticide residues, were not removed from the runoff. During the first furrow irrigation of the season (soon after cultivation), 39% of the sediment load entering the pond was removed. In the second measured irrigation, sediment removal was insignificant. The effectiveness of sediment traps was found to be limited by the time available for suspended sediments to settle out of the runoff before discharge. Sediment basins may be ineffective with finer soils at higher runoff rates. Long (2010) suggests settling basins of various size based on Stokes' Law. Clay particles carry the bulk of the adsorbed pesticide residues. A settling basin of 57 acre feet would be required to provide enough time to settle these small particles out of tailwater runoff at 50 gallons per minute.

A study was conducted in the Central Valley to measure pyrethroid removal by a tailwater recovery pond (Markle 2009). A pyrethroid, lambda-cyhalothrin, was applied to a border-check-irrigated almond orchard at the rate of 0.04 pounds of active ingredient per acre. Runoff water was measured for volume, sediment, and pyrethroid residue concentration as inflow and outflow in a recycling pond that was 19 feet by 16 feet by 7 feet deep. About 15% of the irrigation onflow water exited the field as runoff. The pond reduced the sediment in the water by 80% and pyrethroid residues by 61% (inflow to outflow). The difference in the removal efficiencies for sediment and pyrethroid residues was probably due to the adsorption of lambda-cyhalothrin residues to lighter-weight clay particles that did not have a chance to settle out in this trial. Removal efficiency may have been further improved with lower flow rates or longer retention times in the pond.

Vegetative filter strips

A vegetative filter strip is an area of dense grass or other vegetation, natural or planted, between a field and a nearby waterway. Filter strips protect water quality by capturing and filtering surface runoff from cropland. Tall, sturdy, hardy perennial grasses are preferred, since once established they withstand the force of runoff water and summer drought. The width of the strip required to effectively remove sediments depends on the slope of the area draining into the strip. For slopes of less than 1%, the strip should be at least 25 feet wide.

Vegetative filter strips function in three distinct layers—surface vegetation, root zone, and subsurface horizon (Grismer et al. 2006). As surface flow enters the strip, water is infiltrated until the shallow surface and shallow subsurface is saturated. This infiltration phase is most important for reducing offsite movement of residues. Pesticide or other chemical residues are trapped by soil constituents and organic matter, allowing degradation to occur. The remaining flow volume and velocity is decreased, reducing sediment transport. Sediment particles are trapped on the surface litter layer, which is high in organic matter. As the process continues, water moves through the subsurface horizon, further decreasing the volume of runoff.

Effectiveness in removing pesticide residues

The chemical characteristics of a given pesticide determine the type and amount of residue reduction achievable with vegetative strips or ditches. Organophosphate pesticides tend to be water soluble, while pyrethroids are virtually insoluble in water and are primarily adsorbed to sediments. Diazinon, an organophosphate with high solubility in water, can be expected to remain in solution for long periods (Bondarenko and Gan 2004). Previous evaluations of the effectiveness of vegetation for removing diazinon from water have shown mixed results. Watanabe and Grismer (2001) evaluated diazinon removal by vegetative filter strips under controlled laboratory conditions and found that the majority of diazinon removal occurred via infiltration into the root zone and adsorption to vegetative matter. However, 73% of the applied diazinon was detected in the runoff water leaving the vegetative strip. Long et al. (2010b) found that reduction in sediment load was directly related to pyrethroid residue removal by the filter strip. Sediment runoff was reduced by 62% when furrow runoff water passed through a well-established vegetative strip planted to either tall fescue or a perennial ryegrass and tall fescue mixture that represented 2.8% of the field being irrigated. They recommend 0.03 acres of vegetative filter per 100 gallons per minute of tailwater to significantly improve the water quality of field runoff. It should be noted that a vegetative filter strip is used once per irrigation, not for successive sets as would a vegetative ditch.

Vegetative drain ditches

Drainage ditches can be vegetated with plant material that help capture sediments and other sediment-absorbed pollutants and also provide for some water infiltration (fig. 12). The common type of a vegetative drain ditch is a V-shaped ditch 2 to 3 feet deep and 4 feet wide at the top. Short, sturdy, hardy perennial grasses such as dwarf fescues and perennial ryegrass are preferred, since once established they withstand the force of runoff water and summer drought conditions. Vegetation in the ditch can also be resident, such as rushes and bermudagrass. Residue removal efficiency is strongly influenced by runoff flow rate per unit of ditch wetted area. Higher flow rates reduce the removal efficiency.

Figure 12. Vegetated drainage ditch. Photo courtesy UC ANR.

Effectiveness in removing pesticide residues

Anderson et al. (2008) found that a vegetative ditch containing aquatic vegetation removed only 4% of diazinon in contaminated runoff. Moore et al. (2008) used a simulated runoff event to evaluate removal of diazinon in vegetative ditches in Yolo County, California. They described reductions in diazinon runoff using a V-shaped vegetative ditch, but significant concentrations of diazinon remained in the system outflow after five hours. Essentially, diazinon levels were not reduced in runoff water that did not infiltrate into the root zone of the ditch

Chlorpyrifos, another organophosphate, is more hydrophobic than diazinon. Gill et al. (2008) applied chlorpyrifos at 1 pint per acre and found a 40% reduction in the water column concentration after passage through a vegetative ditch, though the residue concentration in the outflow water was still 33 times over the water quality standard of 15 parts per trillion (ppt). Anderson et al. (2008) found an average 35% reduction in chlorpyrifos concentration in two evaluations after passage through a vegetative ditch containing aquatic vegetation. On the other end of the spectrum, Cole et al. (1997) found vegetative filter strips to be effective in reducing 62 to 99% of chlorpyrifos residues in runoff water. Local conditions, including runoff flow rates, size of the vegetative area, and the initial residue concentration, appear to have strongly influenced the effectiveness of these studies.

Because of their hydrophobic nature, pyrethroids adsorb readily to plant surfaces and soil particles and are therefore easier to remove from runoff water than are organophosphates (Moore et al. 2001; Schulz 2004). Moore et al. (2008), for example, found that vegetation was much more effective at removing the pyrethroid pesticide permethrin than the organophosphate diazinon. Anderson et al. (2008) found nearly 100% reduction of permethrin after treatment in a vegetative ditch. Additionally, Gill et al. (2008) found a 25% reduction in pyrethroid (lambda-cyhalothrin) residues after moving runoff water through a vegetative ditch.

Tailwater Collection and Recycling

Tailwater (runoff from the end of a field) is most often associated with surface irrigation (furrow and border-check systems), since well-designed sprinkler and drip irrigation systems should not produce tailwater runoff. Tailwater collection and recycling is an excellent management practice for improving irrigation efficiency and minimizing tailwater impacts.

Figure 13. Tailwater collection in tomatoes. *Photo:* J. K. Clark.

If a new tailwater return system is being planned, management is a key factor in its design. Tailwater generated by irrigation practices is usually pumped from the capture pond through a pipeline to where it will be reapplied (fig. 13). Such a system, when well operated, maximizes irrigation efficiency and minimizes environmental impacts.

Advantages and disadvantages of a tailwater return system

Advantages

- Minimizes offsite environmental impacts of tailwater potentially containing pesticide and fertilizer residues.
- Improves irrigation efficiency since tailwater is reused as irrigation water.
- May reduce water costs.
- Removes standing water that can cause crop loss and weed infestations.

Disadvantages

- Can be expensive to install, maintain, and operate (NRCS cost sharing programs are available in many areas).
- Takes land out of production for the pond and other tailwater recovery system components.
- Requires careful management and timely recycling of tailwater pond contents.

Tailwater Return System Management

There are numerous ways of managing tailwater return systems, and their management is often constrained by the system design. See Schwankl et al. 2007b for information on design, construction, costs, and operation; see NRCS 2007 for further information on design and operational standards.

Treatment of Runoff Water

Runoff water can be chemically treated to reduce pesticide residues. This treatment can be done in the furrow or in a holding basin. Two products have been shown to be effective for this purpose: polyacrylamide (PAM) for reducing pyrethroid-laden sediments and Landguard OP-A Enzyme for treatment of runoff water containing soluble organophosphate pesticides. Work is underway to develop enzymes to treat pyrethroid residues.

Polyacrylamide (PAM)

PAM is effectively reduces pesticide residues attached to soil particles (generally, pyrethroids) that leave the field or are generated in a tailwater ditch through erosion during irrigation. Studies have shown that this erosion occurs along the field length during furrow irrigation. PAM is a solid or liquid water-soluble polymer that flocculates sediments, binding them together and causing them to drop out of the water. When added to runoff water, PAM can mitigate transport of sediment-adsorbed pesticides from furrow-irrigated fields.

Liquid PAM can be constantly injected into the irrigation water, constantly deposited in granular form into turbulent irrigation ditch water, or applied to the furrow as dry tablets (40% PAM) or granules (89% PAM), where it is slowly dissolved by irrigation water. In-furrow applications are generally less expensive and easier than liquid or granular PAM applications to the inflow ditch or piped water. However, in-furrow applications do not allow for precise control of product concentration (Long et al. 2010a). Table 8 compares the cost of using dry formulations of PAM on an 80-acre furrow-irrigated row crop planted on 5-foot beds. In this example, the time for the water to reach the end of the 1,200-foot furrow is 12 hours with a flow rate of 11 gallons per minute irrigating water reached the end of the furrow. The lowest cost was for granules placed in the furrow, while the highest cost was for liquid PAM.

Table 8. Cost comparisons for different single irrigation PAM dry formulations for a typical 80-acre furrow-irrigated row crop planted on 5-foot beds.

Application method	Cost per acre	Comments
Granules placed in furrow	$1.24	1 oz of granules per furrow
Tablets placed in furrow	$6.38	Two tablets per furrow (50g tablet)
Granules injected into irrigation water	$3.36	Target concentration = 5 ppm; injection time = 12 hr (time needed for water advance to end of furrows)

Source: Long et al. 2010a; adjusted for 2011 costs.

Note: *Cost per acre is based on the gross acreage of the 80-acre field.

At a furrow length of 1,200 feet, 60-inch beds would require about 1 ounce of granules, or 2 tablets, per furrow. Granules are applied in a “patch” in a 3-foot section of the furrow, far enough from the furrow head to prevent sediments from covering the patch. In the Pacific Northwest, placement 5 feet from the furrow head was successful (Sojka et al. 2007). In California, the patch was quickly covered and not effective, whereas placement 100 feet down the furrow was successful (Long et al. 2010b). Once applied as a patch, PAM seems to be effective for a few irrigations. If the soil is disturbed by cultivation, PAM must be reapplied. Typically, one tablet is applied the head of the furrow (as with granules), and one is applied in the middle of the furrow. PAM is more effective in finer-textured soils and in irrigation water that contains calcium and low levels of sodium.

The cost of season-long control is difficult to estimate because the effectiveness of a single application varies with the number of irrigations and the number of field cultivations. Liquid PAM that contains oil-based carrier material is available, but the cost per acre is high and the product can be toxic to certain aquatic life at recommended field application rates (Weston et al. 2009).

Effectiveness in removing pesticide residues

PAM has been shown to be effective in reducing sediments when applied in irrigation furrows. In studies in the Pacific Northwest on furrow-irrigated soils over a 3-year period, Sojka et al. (2007) found that application of PAM at 1 pound per irrigated acre (about

10 ppm) eliminated 94% of sediment in field runoff. A seasonal rate of 3 to 7 pounds per acre was used, depending on the crop and number of cultivations. One of the mechanisms of decreases sediment loss is increased infiltration of irrigation water into the field, because PAM effectively reduces runoff volume (Trout et al. 1995). Sojka, using the recommended PAM application rate of 10 ppm, found increases in infiltration of 15 to 50% compared with untreated controls. In a California study conducted on loam and clay loam soils, Long et al. (2010b) found no PAM effect on infiltration into loam and clay loam soils at a lesser application rate (assumed to be near 2 ppm). Long et al. also found that an application rate of 1 to 2 ounces per 600-foot furrow using the "patch method" reduced sediment loss from 57 to 97% in numerous trials where furrow flow rates averaged 17.5 gallons per minute. They found greater than 80% sediment control in 60% of the trials. The concentration of a pyrethroid, lambda-cyhalothrin or zeta-cypermethrin, was reduced by the same amount.

Landguard OP-A degradation enzyme

Runoff water containing organophosphate insecticide residues can be treated with Landguard OP-A, a degradation enzyme, to reduce or eliminate residues in runoff water before it exits the farm. This product promotes the breakdown of most organophosphate pesticides into less-toxic metabolites. The powdery enzyme is mixed with water into a stock solution and usually applied to runoff water in the tailwater ditch, but it can also be applied to a holding basin. The enzyme treatment rate, residue concentration, and time available before runoff discharge must be carefully managed to ensure degradation at a minimum material cost. Increasing the time between treatment and runoff discharge allows for a lower enzyme application rate. The key factor in determining the correct application rate is the maximum expected runoff rate. The runoff rate is typically not constant over time. When using a single application rate based on the maximum estimated flow rate, overapplication is likely at the lower flows that typically occur at the beginning and end of runoff. Additionally, the practice of irrigating more checks during a nighttime set can lead to different peak flows of different duration.

A comparison was made of the amount of enzyme required for single maximum-rate application for an entire runoff period and for a variable rate as required by the flow rate, essentially keeping the application rate constant (Prichard and Antinetti 2009). A single rate for the maximum volume during the first irrigation resulted in an application rate that was more than double the amount needed. Estimating that the next set would have nearly the same runoff flow rate and using the same application rate, the second set required over 6 times the rate of a correctly managed variable system due to the lower amount of runoff.

Effectiveness in removing pesticide residues

A field trial in California found chlorpyrifos in runoff at a concentration near 10 ppb prior to Landguard OP-A treatment; 12 minutes after the enzyme was added at a rate of 4.3 ounces per acre-foot of runoff water, the chlorpyrifos concentration declined to 0.4 ppb (Weston and Jackson 2010). At higher rates, chlorpyrifos became undetectable. The effects of the enzyme on chlorpyrifos-related toxicity are equally dramatic. The enzyme reduces chlorpyrifos toxicity to *Hyalella azteca* (a test organism) by at least 70-fold compared with untreated water. Without the enzyme, the concentration of chlorpyrifos required to kill half the test organisms was 141 ppb; with enzyme, none of the test organisms were killed.

A team led by Brian Anderson of the UC Davis Marine Pollution Studies Laboratory applied Landguard OP-A at the rate of 4.3 ounces per acre-foot of runoff water directly into a drainage ditch containing diazinon residues (Anderson et al. 2008). Samples of runoff water were collected from the ditch before application and 107 feet downstream from the electronic application unit (fig. 14). In multiple trials, Anderson found that samples treated with Landguard OP-A removed all detectable diazinon, and all were nontoxic to *Ceriodaphnia dubia*, another aquatic arthropod test organism.

A Risk Analysis Case Study: Potato Aphid

The management practices presented in this publication have been proven to effectively reduce the offsite movement of pesticide residue in runoff from tomato field operations. The following case

Figure 14. Anderson trial showing vegetated ditch and electronic dosing unit, 2008. *Photo* by B. Anderson

study expands on the example introduced in the "Overview of Risk Evaluation," above, and illustrates how specific changes can be made in field operations to reduce pesticide movement from the field. For further information on management options given below, see the discussions in earlier sections of this publication.

Crop: Tomato, 40 acres, conventional tomato production.

Topography: 0.15% slope.

Soil: Hollenbeck silty clay loam, which tends to crust, limiting the water infiltration rate. Bed up in the fall.

Irrigation system: Furrow irrigation.

Irrigation water: pH 7.5, EC 0.2 dS/m.

Irrigation runoff: About 17% of the applied water.

Drainage: Runoff moves to a drainage ditch at edge of field, then into a larger creek.

Pesticide mixing and loading: A pesticide mixing and loading area is located 40 feet from the drainage ditch.

Pest: Potato aphid (*Macrosiphum euphorbiae*).

Pest detection: 60% of leaves sampled from below the highest flower were infested on July 15, 9 weeks prior to harvest.

We begin the risk assessment with Flowchart 1 (see the flowcharts at the end of this publication), considering possible routes by which pesticide could move off the field and the operations or conditions that may contribute or mitigate the risk. We will determine whether a risk exists for irrigation runoff, storm water runoff, and spray drift, then review management practices to mitigate the risk.

Irrigation Runoff Risk

In our example, furrow irrigation results in about 17% of the applied water being run off, which poses a risk of moving chemicals to a surface water ditch and on to a creek.

Proceeding to Flowchart 3, the next step is to evaluate IPM practices used to control potato aphid.

Integrated pest management: Potato aphid

The following information on potato aphid in tomato was adapted from the UC IPM Tomato Pest Management Guidelines, available at the UC IPM website, http://www.ipm.ucdavis.edu/PMG/.

The potato aphid has both a pink and a green biotype. This aphid is much larger than the green peach aphid and has a more elongated body. It is generally found on the terminals of tomato plants later in the season than the green peach aphid and is also considered to be more damaging.

High populations of potato aphid can distort leaves and stems, stunt plants, and cause necrotic spots on leaves. These aphids also secrete a large amount of honeydew, which promotes sooty mold on foliage and fruit. Plants are particularly susceptible to yield losses from high infestations from 6 to 8 weeks before harvest. Yield loss from these high populations of potato aphid declines substantially as harvest approaches unless aphid densities reduce leaf area enough to permit sunburn.

Aphid monitoring

Monitor potato aphids from bloom to early fruit set by picking the leaf below the highest open flower on 30 plants selected at random throughout the field. Record the presence or absence of potato aphids on each leaf while noting natural enemies. Treatment is warranted if 50 to 60% or more of the leaves are infested. If 50% of such leaves are infested from 6 to 8 weeks before harvest, the resulting loss is about 1 ton per acre for processing tomatoes.

Management options

Biological control. Naturally occurring parasites and predators of the potato aphid are common and can provide control. Monitor the proportion of aphid mummies relative to unparasitized aphids and the number of predators such as lady beetles, lacewing larvae, and syrphid larvae. If the proportion of mummies is increasing or predators appear to be gaining control and aphid populations are not yet damaging, avoid sprays that disrupt these natural enemies.

Tolerant varieties. There is considerable difference in tomato variety susceptibility to potato aphid feeding. Varieties containing the Mi gene, which confers resistance to nematodes, have been reported to be more tolerant of potato aphid infestations than varieties that do not contain the gene. However, this resistance no longer appears to be as effective as it once was, particularly against the pink form of the potato aphid.

Organically acceptable methods. The use of tolerant varieties, biological control, and sprays of herbal oils, pyrethrin, or insecticidal soap are acceptable for use on an organically certified crop. Repeated applications may be necessary for control.

Chemical control. In our example, the potato aphid has reached the threshold level at a critical period during fruit set. A chemical control spray is warranted to avoid yield losses due to aphid feeding. After this initial spray, continued monitoring will be needed to determine whether further applications are needed.

Selecting pesticides to reduce water quality risks

Continuing to work our way through Flowchart 3, the next step is to select an effective pesticide that has minimum risk to water quality.

Potato aphid treatment options are derived from the UC IPM Tomato Pest Management Guidelines (http://www.ipm.ucdavis.edu/PMG) (table 9), combined with the potential for runoff risk and overall risk from table 2. The options include two organophosphates and two pyrethroids, a carbamateand, and a neonicotinoid.

Many organophosphates are highly water soluble and subject to runoff risk, while pyrethroids are highly hydrophobic and adsorb readily to soil sediments, which are also subject to offsite movement.

Table 9. Common treatment options for potato aphid for conventional tomato production

Chemical	Trade name	Chemical class	Solution runoff potential[*]	Adsorption runoff potential[†]	Overall runoff risk[‡]
acetamiprid	Assail	neonicotinoid	—	—	—
dimethoate	Dimethoate	organophosphate	low	low	low
lambda-cyhalothrin	Warrior	pyrethroid	low	intermediate	high
lambda-cyhalothrin plus acetamiprod	Warrior plus Assail	Pyrethroid plus neonicotinoid	low	intermediate	high
methamidophos	Monitor	organophosphate	low	low	low
methomyl plus fenopropathrin	Lannate plus Dannitol	carbamate plus pyrethroid	intermediate	low	moderate

Notes:

[*] Likelihood that the active ingredient will transport from the area of treatment as dissolved chemical in runoff.

[†] Likelihood that the active ingredient will transport from the area of treatment as attachment to soil or sediment particles in runoff.

[‡] Overall likelihood to cause negative impact on surface water quality as a product of the runoff potential and the aquatic toxicity of the pesticide.

— Not known.

Mixing and loading near surface water

The next consideration in Flowchart 3 for managing potato aphid is to consider pesticide mixing and loading practices and their impact on surface water quality. The mixing and loading site in our example is within 50 feet of a surface water ditch. Mixing and loading practices include not overfilling the tank, triple-rinsing containers and adding the rinsate to the tank, and rinsing the tank and applying the rinsate to the field. The use of a concrete pad with a catchment sump is also a good way to reduce risks from mixing and loading near surface water sources.

Irrigation management

The next step in our assessment in Flowchart 3 is to consider changes in irrigation management.

Irrigation scheduling

Scheduling irrigations using evapotranspiration reference (ET_o) and the coverage of the crop canopy can reduce the volume of water applied and therefore the amount of runoff in furrow and pressurized irrigation systems. However, it is much easier to apply a desired amount of water using pressurized systems such as drip irrigation. Use soil-based moisture monitoring to verify calculations and to make sure that the volume of water applied is sufficient for crop water use.

Improve irrigation uniformity

The runoff volume can be reduced in furrow irrigation by matching the inflow rate to the infiltration rate and optimizing the irrigation cutoff point. Blocking furrows by making small soil or plastic dams in the length of the furrow can improve uniformity while increasing infiltration and reducing runoff volume.

Reduce runoff volume

Manage irrigation system to reduce runoff. The runoff volume can be reduced in furrow irrigation by matching the inflow rate to the infiltration rate and optimizing the irrigation cutoff point to achieve good uniformity.

Improve water infiltration. The irrigation water in our example field has salinity (EC_w) of 0.2 dS/m, indicating a "pure water" infiltration problem. Adding gypsum and a solutionizer to the irrigation water can improve water infiltration and may reduce runoff.

Convert to pressurized irrigation. At sites with runoff risks, changing from surface irrigation to pressurized irrigation is recommended when possible. When properly managed, pressurized irrigation systems cause no irrigation water runoff, effectively reducing the risk of offsite movement of pesticide residue.

Runoff water capture and recycling

Sediment basins and recycling runoff. Sediment basins can be used to capture runoff and reduce sediment load. Recycling runoff water to the delivery system can completely eliminate the runoff.

Vegetative strips and drain ditches. Properly designed and constructed vegetative strips can filter sediments from runoff. Take care to create a large enough strip or ditch to reduce runoff velocity.

Runoff water treatment. Runoff water containing residues of organophosphates can be treated with enzymes that rapidly degrade the material.

- **Landguard OP-A**, an organophosphate degradation enzyme, can reduce or eliminate residues in runoff water before the water exits the farm. This product promotes the breakdown of most organophosphate pesticides into less-toxic metabolites. The powdery enzyme is mixed with water into a stock solution and applied to runoff water in a tailwater ditch or holding basin.
- **PAM** (polyacrylamide) is a solid or liquid water-soluble polymer that flocculates sediments, binding them together and causing them to drop out of the water. When added to runoff water, PAM can mitigate transport of sediment-adsorbed pesticides contained in runoff.

Application Near Surface Water Sources Risk (Drift)

Now that we have evaluated the irrigation runoff risks, we go back to Flowchart 1 to evaluate the drift risk. Our example field is located near a ditch that drains to a surface water source and is therefore a significant risk. We will consider reducing spray drift that could enter the drainage ditch or creek near the example field. See the following drift management options in Flowchart 5.

Application conditions

Delay treatments near ditches and surface water bodies until wind is blowing away from these and other sensitive areas.

Application equipment

Use as coarse a spray as possible (250 to 400 microns or larger) without sacrificing good canopy coverage. Droplet size is one of the most important factors affecting drift. Use low-drift nozzles that produce larger droplet sizes. Fitting a sprayer with air induction nozzles instead of standard nozzles reduces spray drift up to 50%.

Product choice

Use drift control or drift reduction spray additives. These materials are generally thickeners that minimize the formation of droplets smaller than 150 microns. They also help produce a more consistent spray pattern and aid in deposition. Choose materials that are least disruptive to aquatic life for use in buffer zones.

Buffer zones

Maintain adequate buffer zones between the treated site and sensitive areas to ensure that pesticides do not drift from the target area. Follow the directions on the pesticide label for the size of the buffer zone.

Change application method

Aerial application has a larger drift potential than ground application. When the risk of drift is present, use ground application, which also requires a smaller buffer zone.

Storm Water Runoff Risk

Now that we have evaluated the risk of chemical application near surface water, we go back to Flowchart 1 to evaluate the storm water runoff risk.

Improve water infiltration

In the case study, the field is bedded up in the fall, posing a risk that rainfall can move sediment offsite in runoff. The sediments can contain adsorbed pesticides, most likely pyrethroids. Go to Flowchart 4.

Chemical amendments used to improve water infiltration

The addition of chemical amendments to water or soil can improve water infiltration. Most chemical amendments work by increasing the total salt concentration or decreasing the sodium adsorption ratio (SAR) of the soil-water. These actions enhance aggregate stability and reduce soil crusting and pore blockage.

Calcium materials. Adding calcium salts to soil and water increases the total salinity and the soluble calcium. Calcium salts commonly used on alkaline (high-pH) soils include gypsum ($CaSO_4$), calcium chloride ($CaCl_2$), and calcium nitrate ($CaNO_3$). Gypsum is the most common calcium material applied in the fall prior to bedding up. Surface applications are most effective when gypsum is applied at rates of 1 to 2 tons per acre.

Acids and acid-forming materials. Commonly applied acid or acid-forming amendments include sulfuric acid (H_2SO_4) products, soil sulfur, ammonium polysulfide, and calcium polysulfide. The acid from these materials dissolves soil-lime to form a calcium salt (gypsum), which then dissolves in the irrigation water to provide exchangeable calcium. The acid materials react with soil-lime the instant they come in contact with the soil. Materials with elemental sulfur or sulfides must undergo microbial degradation in order to produce acid. This process may take months or years, depending on the material and particle size (in the case of elemental sulfur). Since these materials form an acid via the soil reaction, they reduce soil pH if applied at sufficiently high rates.

Managing soil organic matter to reduce runoff

Soil organic matter helps stabilize soil aggregates by increasing the number of exchange sites in the soil matrix and encouraging microbial activity. Soil microbes that decompose soil organic matter produce polysaccharides and polyuronides, which act as binders to stabilize aggregates, improving porosity and water infiltration. Over time, continued cultivation and the use of herbicides reduces the organic matter content and aggregate stability of soils. These changes can reduce water infiltration and increase the runoff potential.

It is difficult to increase and sustain soil organic matter under the warm, semiarid conditions that prevail in most of California, which favor rapid organic matter decomposition. Organic matter additions aimed at improving or sustaining aggregate stability and water infiltration must be incremental and continual to be effective. Growers can achieve this in the following ways.

Crop residues. After harvest, residues of field crops that are shredded or incorporated can add organic matter and a certain amount of nutrients to the soil. Crop residue biomass in California's Central Valley ranged from 9,560 pounds per acre for corn after grain harvest to 570 pounds per acre for onions; for tomato, the average was 2,880 pounds per acre. Wheat biomass was 4,800 pounds per acre after grain harvest, but after baling, only 670 pounds remained (Mitchell et al. 1999).

Manure and other organic materials. With proper handing and management to avoid the risk of crop contamination by human pathogens, animal manures or compost can help increase soil organic matter content and improve water infiltration. However, the application of manures is currently uncommon due to their limited availability.

Protect soil surface using cover crops. Cover crops can help protect the soil surface from droplet impact during winter rainfall and can provide significant organic matter biomass for decomposition and microbial stabilization of soil aggregates. In addition, cover crop residue can slow the velocity of surface water, reducing erosion and subsequent depositional crusting. In one study, a winter cover crop of triticale was planted to bed tops in a tomato field in early November and chemically controlled at a height of about 8 inches in mid-February (Miyao et al. 2004). The result was a 40% reduction in storm water runoff volume and a 70% reduction in runoff turbidity compared with a field with no cover crop. Less-expensive options include using barley or oats.

Runoff water capture and recycling

Sediment basins

A sediment basin or trap consists of an embankment, an emergency spillway, and a perforated pipe riser. The basin may be located at the bottom of a slope where drainage enters a swale or waterway.

Tailwater capture and recycling

Tailwater generated by irrigation practices is most often pumped from the capture pond to where it will be reapplied. Such a system, well operated, maximizes irrigation efficiency and minimizes environmental impacts.

Vegetative filter strips/vegetative drain ditches

A vegetative filter strip is any area of dense grass or other natural or planted vegetation between a field and a nearby waterway. Filter strips help capture and remove waterborne sediments. A common type of vegetative filter strip is a vegetative ditch, typically V-shaped, 2 to 3 feet deep and 4 feet wide at the top. Vegetation can be resident, such as rushes and bermudagrass, or planted, such as rushes, pennywort, creeping wild rye, or red fescue. Vegetative ditches can help reduce chemical contaminants by infiltration, direct adsorption of chemicals to plant surfaces, and promoting sedimentation of particle-bound contaminants.

Runoff water treatment

Polyacrylamide (PAM)

PAM is a solid or liquid water-soluble polymer that flocculates sediments, binding them together and causing them to drop out of the water. When added to runoff water, PAM can mitigate transport of sediment-adsorbed pesticides.

Winter applications of PAM are usually applied as dry tablets (40% PAM) or granules (89% PAM), where it is slowly dissolved by runoff water. The application rate for a 60-inch bed that is 600 feet long would be 1 ounce (or 2 tablets) per furrow. PAM is applied in a "patch" in a 3-foot section near the middle and near the end of the furrow. PAM can also be applied as a patch near the inlet to a sediment basin to help reduce the time for the clay particles to settle out.

Landguard OP-A

Landguard OP-A Enzyme has been shown to effectively treat most soluble organophosphate pesticides in runoff water. This treatment can be done in a tailwater ditch or in a holding basin. Work is underway to develop enzymes to treat pyrethroid residues, but they are unavailable at this time.

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Measurement Conversion Table

U.S. Customary	Conversion factor for U.S. Customary to Metric	Conversion factor for Metric to U.S. Customary	Metric
Length			
inch (in)	2.54	0.394	centimeter (cm)
foot (ft)	0.3048	3.28	meter (m)
mile (mi)	1.61	0.62	kilometer (km)
Area			
acre (ac)	0.4047	2.47	hectare (ha)
square foot (ft2)	0.0929	10.764	square meter (sq m)
Volume			
fluid ounce (fl oz)	29.57	0.034	milliliter (ml)
pint, liquid (pt)	0.473	2.11	liter (l)
pint, dry (pt)	0.55	1.82	liter (l)
quart, liquid (qt)	0.946	1.056	liter (l)
quart, dry (qt)	1.1	0.91	liter (l)
gallon (gal)	3.785	0.26	liter (l)
inch (in; irrigation)	305	0.00328	millimeter
acre-inch (ac-in)	102.8	0.0097	cubic meter (cu m)
acre-foot (ac-ft)	1,233	0.000811	cubic meter (cu m)
cubic foot (ft3)	28.317	0.353	liter (l)
cubic yard (yd3)	0.765	1.307	cubic meter (cu m)
gallon per acre	9.36	0.106	liter per hectare (l/ha)
Mass			
ounce (oz)	28.35	0.035	gram (g)
pound (lb)	0.454	2.205	kilogram (kg)
ton (T)	0.907	1.1	metric ton (t)
pound per acre (lb/ac)	1.12	0.89	kilogram per hectare (kg/ha)
ton per acre (T/ac)	2.24	0.446	metric ton per hectare (t/ha)

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This publication has been anonymously peer reviewed for technical accuracy by University of California scientists and other qualified professionals. This review process was managed by the ANR Associate Editor Chair.

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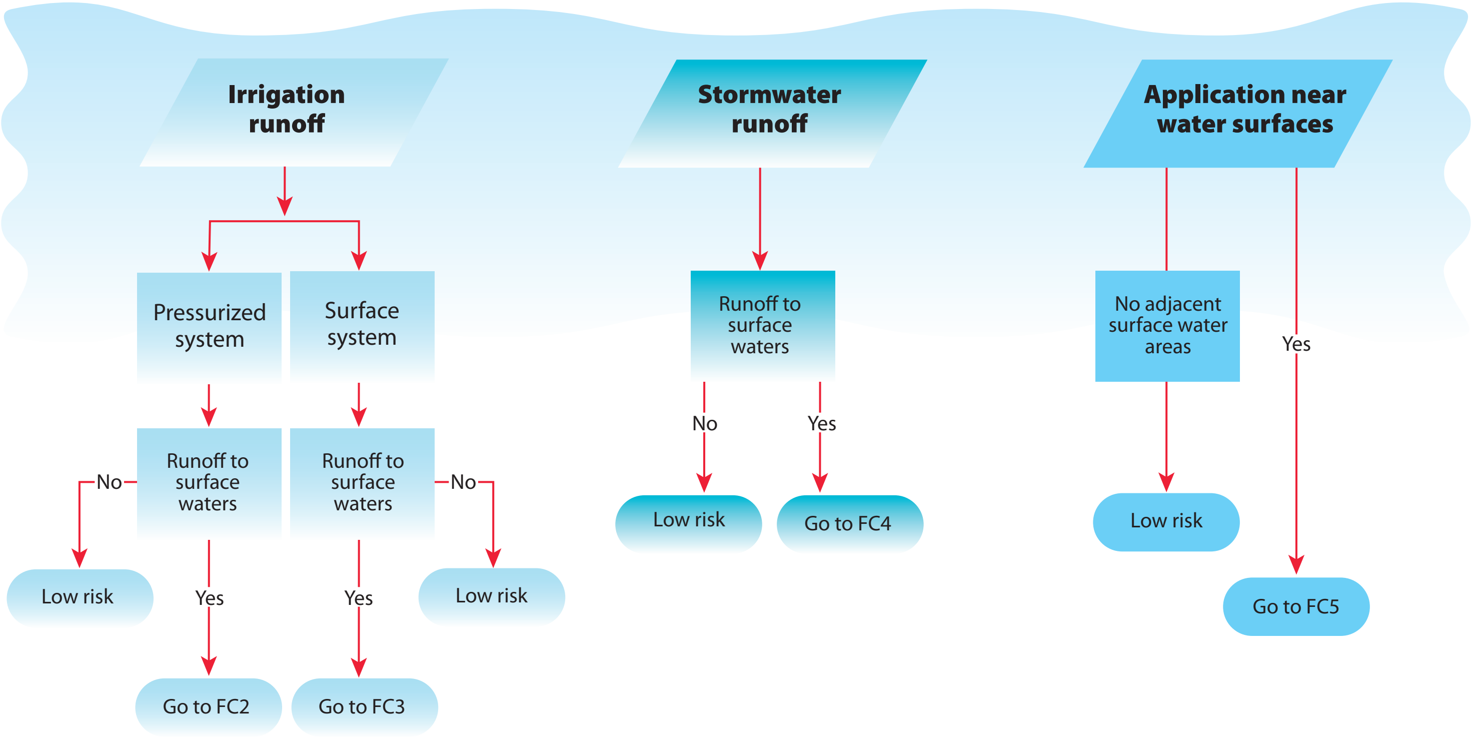
FC1

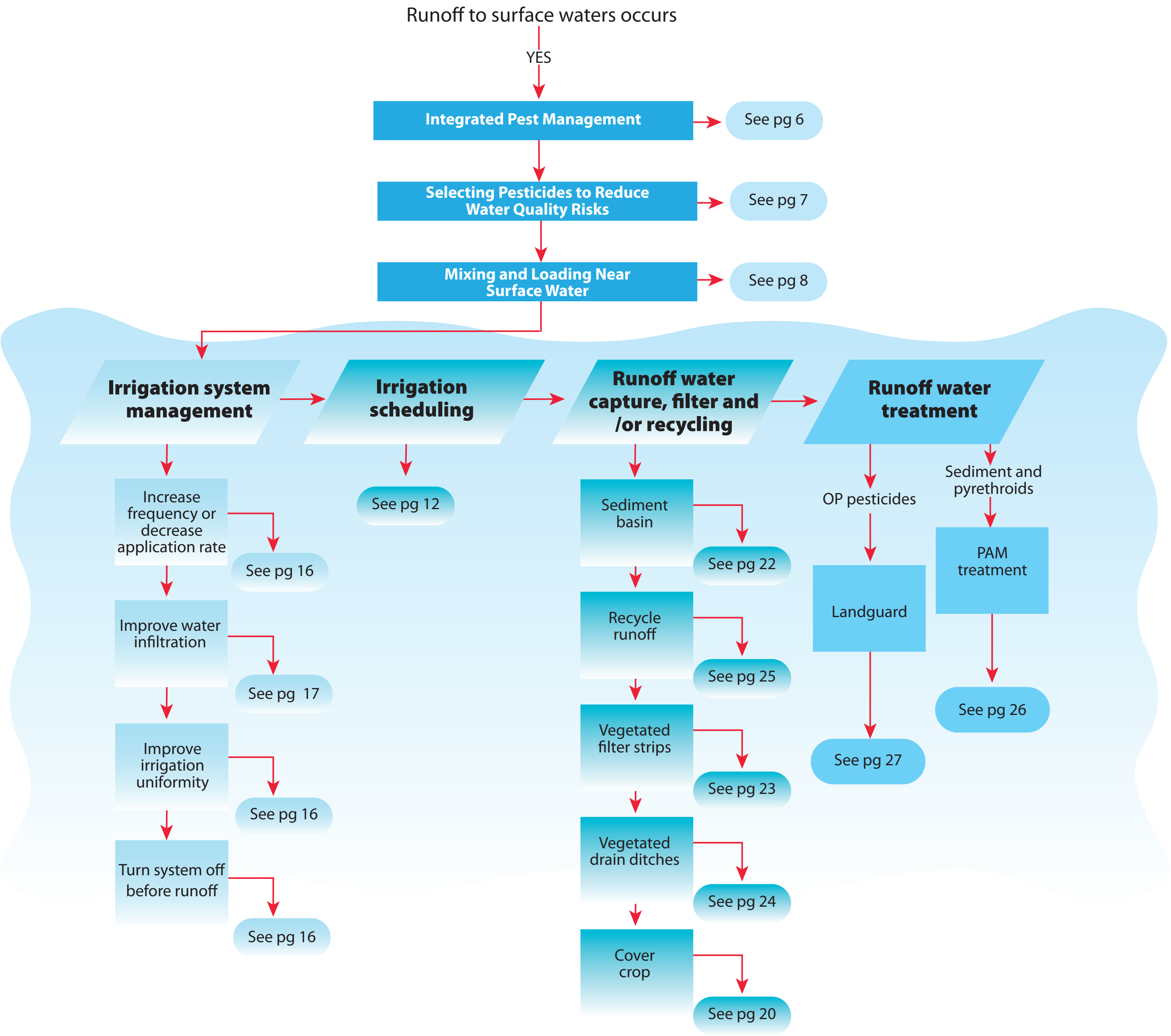
Assessing the Risk of Offsite Movement of Ag Chemicals to Surface Waters

Follow the decision tree from each shaded box below to assess risk, based on your conditions. If the risk is significant, continue on to view management practices that may reduce the risk of offsite movement



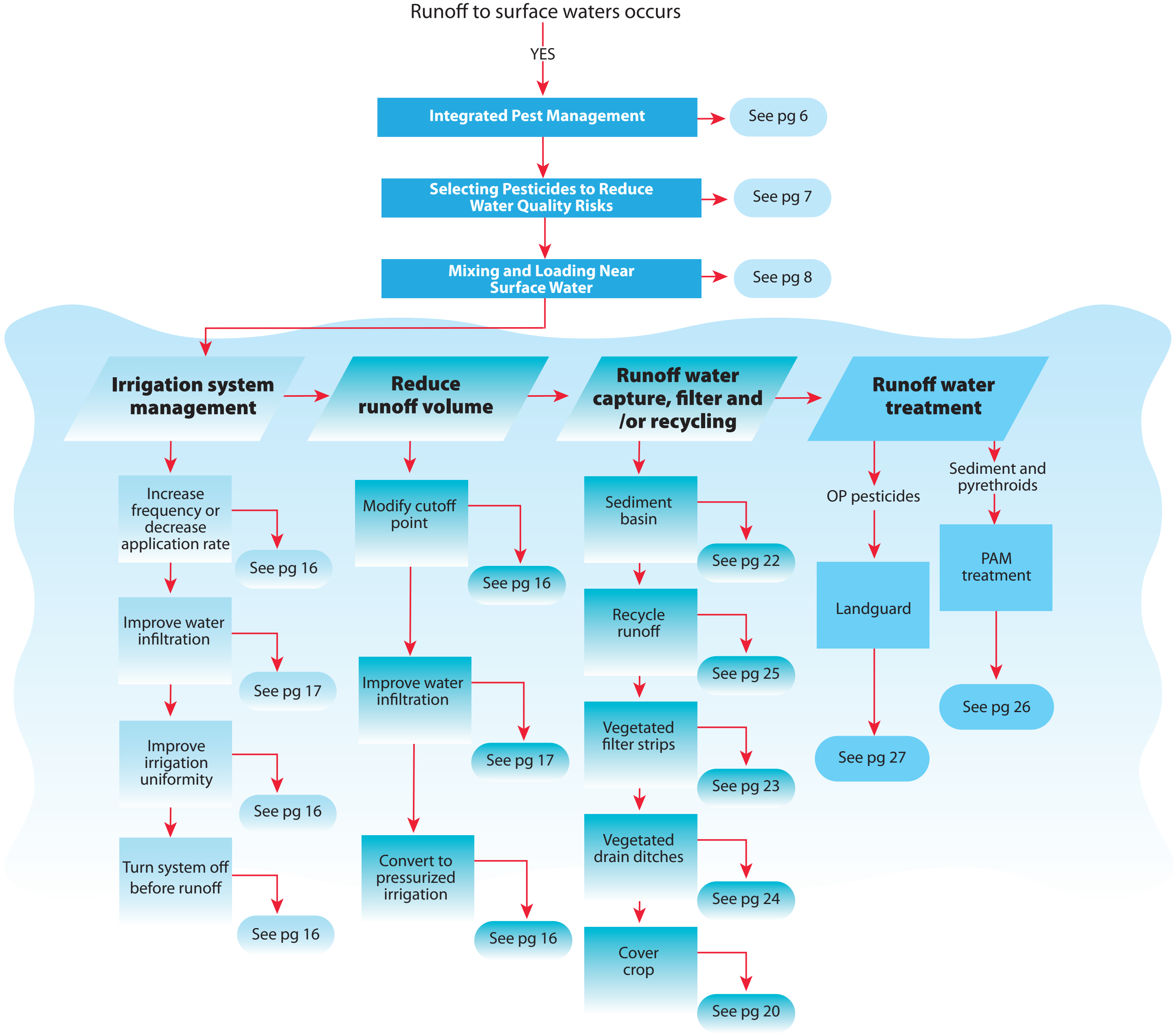
FC2

Reducing the Risk of Offsite Movement of Ag Chemicals in Runoff – Pressurized Irrigation Systems



FC3

Reducing the Risk of Offsite Movement of Ag Chemicals in Runoff – Surface Irrigation Systems



FC4
Reducing the Risk of Offsite Movement of Ag Chemicals
Stormwater Runoff