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Controlling Offsite Movement of Agricultural Chemical Residues: Winegrapes

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This publication provides winegrape growers 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 a self-assessment of the potential risk of offsite pesticide movement using flowcharts for specific management practices and field conditions in winegrapes. 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. 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.

Photo by T. L. Prichard

More detailed information on implementation of many of these practices is available from sources cited throughout (see the reference list 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 in California 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). 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 (TDML) 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 TDML 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 from 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 for toxicity 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. A listing of the active ingredients and trade names for pesticides used in winegrape production can be found in table 1, which lists insecticides with reported use over 100 pounds in California during 2008. Organophosphates and pyrethroids represent 60% of this list. Even though organophosphate pesticides are declining in use each year, they still represent 57% of the total, with chlorpyrifos 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

Table 1. Selected winegrape insecticides with reported use of over 100 pounds in California in 2008 that were registered for use in 2011 (for current information, see the CDPR website http://calpip.cdpr.ca.gov/main.cfm)

Active ingredient common name	Trade name*	Use (lb/yr†)	Chemical class
chlorpyrifos	Lorsban	100,895	organophosphate
imidacloprid	Admire	21,919	neonicotinoid
methyoxfenozide	Intrepid	16,986	diacylhydrazine
buprofezin	Applaud	16,395	unclassified
cryolite	Cryolite	16,160	inorganic
fenpropathrin	Danitol	6,552	pyrethroid
dinotefuran	Venom	5,472	neonicotinoid
phosmet	Imidan	5,348	organophosphate
malathion	Malathion	5,113	organophosphate
methomyl	Lannate	3,310	carbamate
fenamiphos	Nemacur	2,632	organophosphate
diazinon	Diazinon	1,046	organophosphate
clothianidin	Clutch	542	neonicotinoid
spinosad	Success	238	spinosyn
thiamethoxam	Platinum	154	neonicotinoid
dimethoate	Cygon	113	organophosphate

Source: CDPR.

Notes:

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

†Pounds per year active ingredient.

irrigation or storm water runoff can contain pesticide residues, sediment, or nutrients. These discharges in the Central Valley are regulated by the 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 Central Valley water board has established surface water quality standards in each watershed basin plan and 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. 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 waiver 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 3,500 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.

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 coalitions, 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 specific 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 zero in on 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 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 reducing 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 a water quality problem, techniques for physically intercepting, recycling, or chemically treating runoff water can reduce the offsite transport of pesticides.

OVERVIEW OF RISK EVALUATION

For a quick overview of the risk evaluation process, we consider a sample vineyard 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 is presented the final section of this publication. The thick, shaded arrows in the flowcharts indicate the logical progression in considering effective management practices.

Vineyard: Mature Cabernet Sauvignon.

Topography: Undulating topography, 0 to 4% slope.

Soil: San Joaquin Sandy Loam prone to soil surface crusting, which limits water infiltration.

Irrigation system: Pressurized.

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

Proximity to surface water sources: Drainage ditch at the edge of the field contains irrigation runoff from neighboring lands.

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

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. For the purposes of this example, we will consider only the irrigation runoff risk.

- **Offsite movement risk, Flowchart 1.** Pesticides applied to the vineyard may be carried in the runoff that occurs during pressurized irrigation after the pesticide application (fig. 1). This runoff moves to a

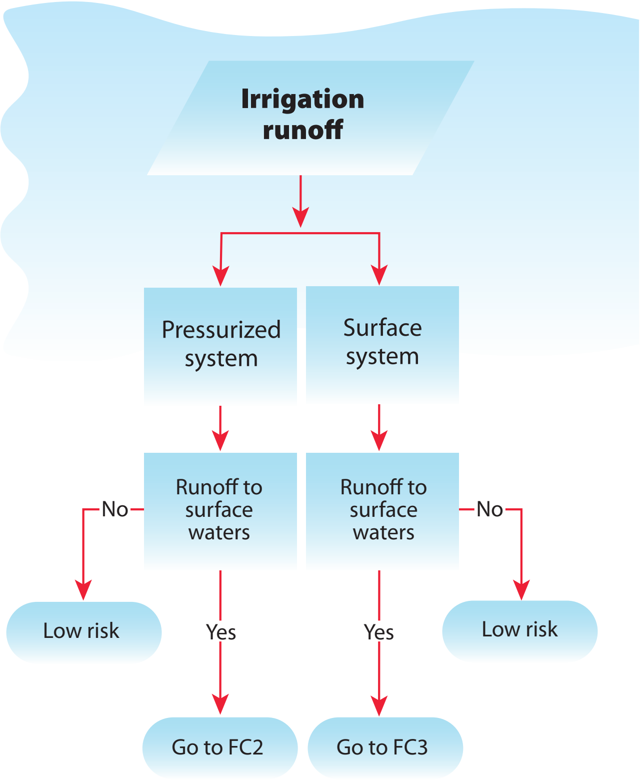

Figure 1. Excerpt from Flowchart 1 showing irrigation runoff risk for sample winegrape vineyard.

drainage ditch and then to surface water. The path for this in Flowchart 1 leads to Flowchart 2.

- **Pressurized irrigation runoff risk, Flowchart 2.** The path from Flowchart 1 leads us to consider IPM practices, pesticide selection, and mixing and loading practices to reduce offsite movement of pesticide residues (fig. 2). At each of these considerations, we are directed to sections in this publication that contain specific management management practices that can be implemented. The flowchart then directs us to consider the irrigation system management, irrigation scheduling, capturing or recycling runoff, and ways that runoff water, if it still occurs, could be treated to reduce any pesticide residues it may contain.
- **Return to Flowchart 1** and repeat this process for storm water runoff and application near surface water sources.

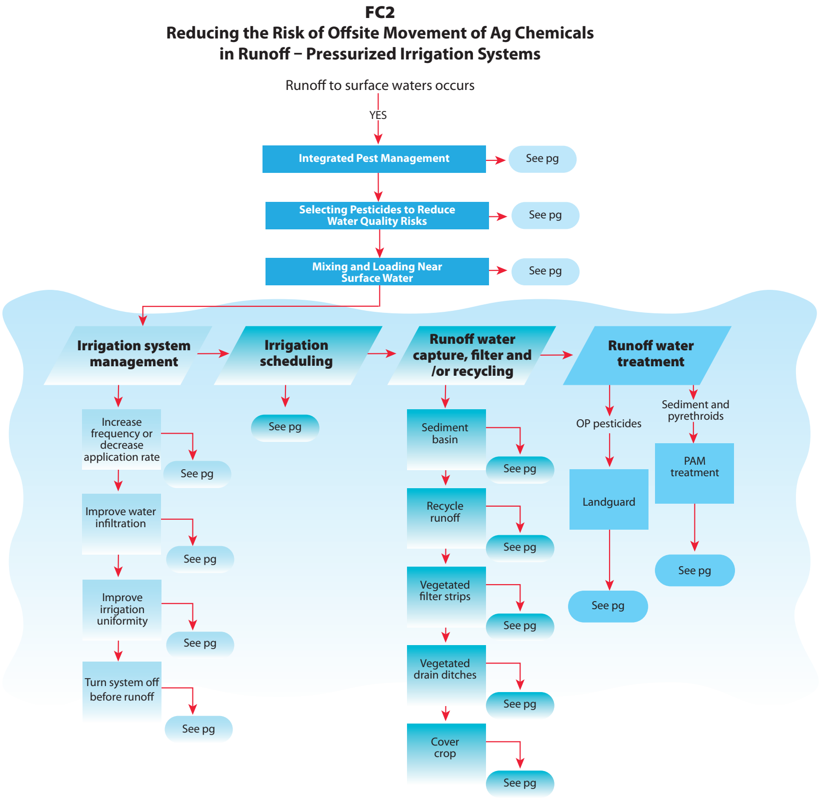

Figure 2. Excerpt from Flowchart 2 showing pressurized irrigation runoff risk.

Management Practices That Reduce Pesticide Contamination of Surface Water

Integrated Pest Management

The University of California Integrated Pest Management Program 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 and disease 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
- 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 Grape Pest Management Guidelines, www.ipm.ucdavis.edu/PMG/
- UC IPM Year-Round Program for Grapes (with annual checklist), http://www.ipm.ucdavis.edu/PMG/C302/m302yi01.html

- *Grape Pest Management*, 2nd edition (ANR Publication 3343; 3rd edition in preparation)
- 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 when selecting the best product to use. Pesticides and pesticide residues can move along several different pathways, depending on the properties of the pesticide, the application method, and conditions at the application site (fig. 3). 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 winegrapes vary in 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 a 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 pesticide'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.)

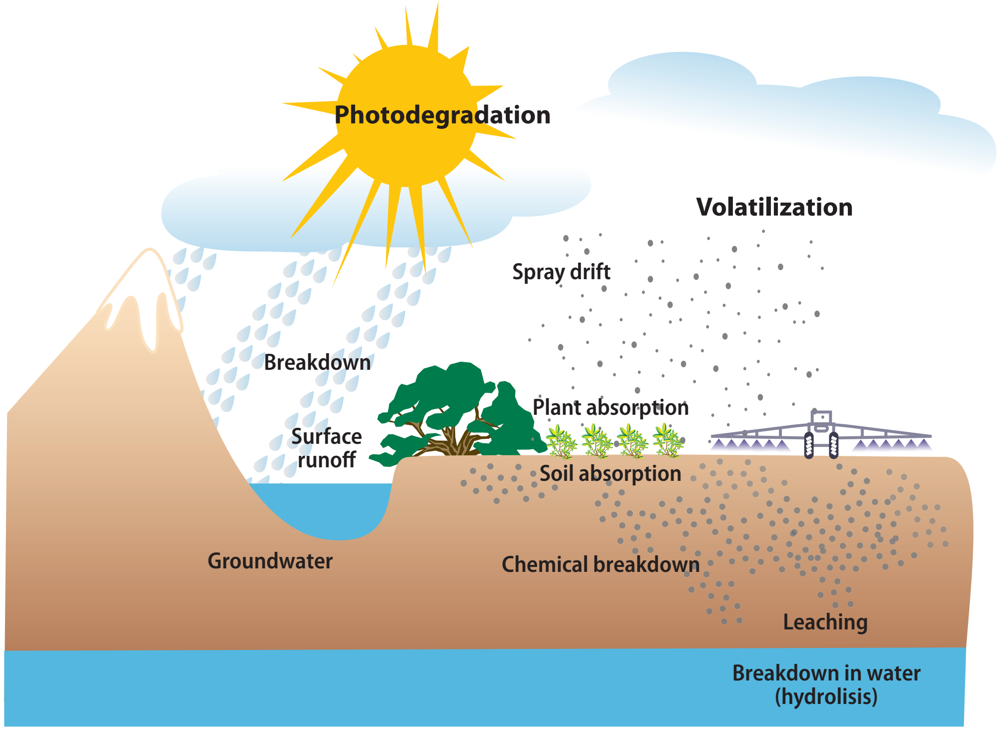

Figure 3. Pesticide movement and degradation.

Table 2. Potential of California-registered winegrape insecticides (2012) to move in solution or as adsorbed particles and overall pesticide runoff risk, in order of highest risk

Insecticide active ingredient (common name)	Trade name	Chemical class	Solution runoff potential*	Adsorption runoff potential†	Overall runoff risk‡
diazinon	Diazinon	organophosphate	high	high	very high
endosulfan	Thiodan	organochlorine	high	high	very high
chlorpyrifos	Lorsban	organophosphate	high	intermediate	very high
abamectin	Agri-Mec, Zephyr	glycoside	high	intermediate	high
permethrin	Pounce	pyrethroid	low	high	high
carbaryl	Sevin	carbamate	intermediate	low	moderate
malathion	Malathion	organophosphate	intermediate	low	moderate
methomyl	Lannate	carbamate	intermediate	low	moderate
phosmet	Imidan	organophosphate	intermediate	low	moderate
fenpropathrin	Danitol	pyrethroid	low	intermediate	moderate
imidacloprid	Provado	neonicotinoid	high	intermediate	low
spinosad	Success, Tracer	spinosad	intermediate	intermediate	low
dimethoate	Cygon	organophosphate	low	low	low
naled	Dibrom	organophosphate	low	low	low
spirotetramat	Movento	keto-enol	intermediate	intermediate	low
methyoxfenozide	Intrepid	diacylhydrazine	high	intermediate	low

Source: Long et al. 2005. Information on insecticides not listed by Long et al. 2005 were developed using the same methodology using WIN-PST and the ECOTOX Database.

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 an 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

Aquatic toxicity rankings were extracted from the U.S. EPA ECOTOX database (EPA 2007). The toxicity to 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 winegrape production (products without a risk category are new and have been categorized in the 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 into 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 (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, at the time of pesticide application or soon thereafter, from the target site to any off-target site. 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.
- 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 be 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

- Treat buffer zones with materials that pose the least risk to aquatic life.
- 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 the pesticide application site. Read the label to determine the size of buffer zone required as related to the rate of active ingredient applied.

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, infiltration rate of the soil, 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 grape production: surface (furrow and border-check) and pressurized (sprinkler and 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. 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 offsite movement of residues. 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 recycling 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: Surface irrigation systems

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

With surface 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

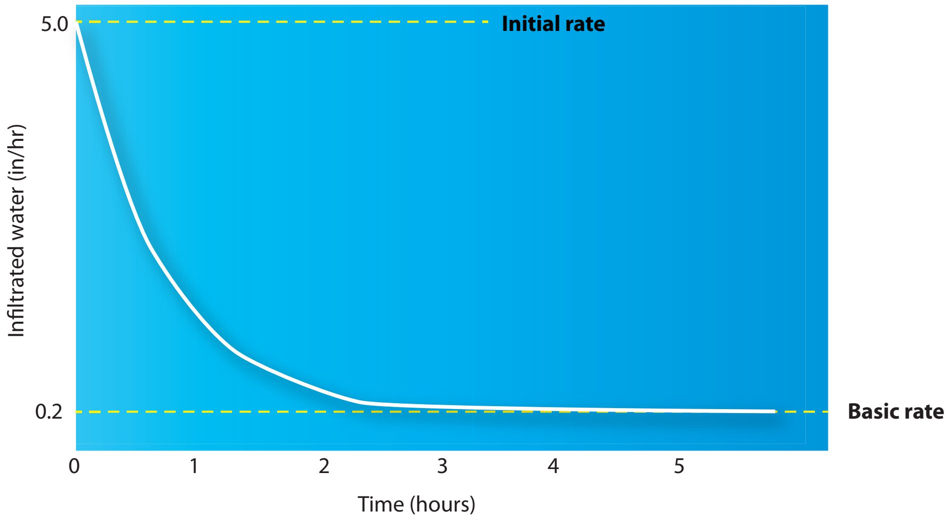

Figure 4. Typical water infiltration characteristics.

water enters the soil is high, primarily because of soil dryness and easy access to the soil pores. As irrigation proceeds, the infiltration rate rapidly declines to a sustained rate (also called the basic rate). Figure 4 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 surface irrigation in vineyards, more water is almost always applied to the head of 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 vineyard 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 or check to get water down the row more quickly and improve irrigation uniformity, but this practice increases runoff volume due to more irrigation time to infiltrate the required water volume.

In general, keeping the furrows or checks as short as practical helps keeps irrigation uniformity high. The tradeoff with short furrows or checks 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 (cfs, 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,

Flow = 2.67 cfs (1,200 gpm)
Irrigation duration = 24.7 hours
Area = 20 acres
Depth of water applied = (2.67 cfs × 24.7 hr) ÷ 20 ac
Depth of water applied = 3.3 inches.

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).

Figure 5. Surface irrigation in a relatively flat vineyard. Photo by L. L. Strand

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. Figure 5 shows a relatively flat vineyard using large furrows that fill quickly, providing reasonable distribution of infiltrated water.

Reducing runoff: Pressurized irrigation systems

Pressurized irrigation used in vineyards includes drip systems and overhead full-coverage sprinkler systems. Overhead sprinklers are not common in vineyards due to concerns about disease and irrigation water nutrient content. Drip irrigation systems allow small amounts of water to be applied slowly and frequently through emitters spaced along polyethylene tubing. When properly designed and operated, these systems apply water uniformly to a relatively small volume of soil and do not create wet conditions that promote disease.

Unlike surface irrigation systems or full-coverage sprinklers where soil water is recharged on an infrequent basis then drawn down by vine use, drip irrigation, by virtue of frequent applications, can be operated to replace water used by the vine. The process occurs on a time scale of a day or a few days. This frequency of irrigation is well suited for deficit irrigation strategies by providing greater consistency in plant water stress and allowing quick response to changing climate conditions.

Irrigation scheduling to meet crop water requirements

Crop water use, or evapotranspiration (ET), is the sum of plant water use (transpiration) and evaporation from the soil surface. Climatic factors affecting the crop evapotranspiration include solar radiation, temperature, wind, and humidity. Plant and soil factors affecting evapotranspiration include plant type, stage of growth, canopy size, health of the plant, and available soil moisture.

Irrigations should

- meet variable crop requirements over the season
- be distributed evenly to maximize irrigation efficiency and facilitate the uptake of nutrients
- minimize saturated soil conditions that encourage diseases and result in excess runoff

Some water in excess of the crop requirement may be needed to maintain a favorable salt balance in the root zone. Proper irrigation scheduling entails applying an optimal quantity that maximizes productivity and quality goals.

Deficit irrigation

In recent years, it has become clear that maintenance of a moderate plant water deficit can improve the partitioning of carbohydrate to reproductive structures such as fruit and also helps control excessive vegetative growth (Chalmers et al. 1981), giving rise to the concept of regulated deficit irrigation (RDI) (Chalmers et al. 1986). RDI is the practice of regulating or restricting the application of irrigation water, limiting vine water use to less than that of a fully watered vine. This practice minimizes the possibility of runoff and the consequent offsite movement of residues.

Successful RDI requires accurate soil moisture or plant “stress” sensing, the ability to estimate crop water demand, and the ability to irrigate frequently. RDI can be a component of a standard irrigation strategy, or it can be used during a drought to curtail vine water use.

Deficit irrigation scheduling. Typical deficit irrigation scheduling relies on an assessment of vine water stress level to begin irrigation (stress threshold), an estimate of full vine water use, and an appropriate level of regulated deficit irrigation (RDI). When used together, this method is called stress threshold RDI irrigation. If irrigation begins too early, water deficits are postponed or eliminated, effectively losing the positive effects of water deficits. One method for determining when to begin irrigation is based on a threshold value of vine water status called leaf water potential. For detailed information on when to begin irrigation and how to measure water deficits, see Prichard et al. 2010. Once the determination is made to begin irrigation and a specific level of deficit irrigation is selected, an RDI schedule can be constructed.

An RDI schedule is established by first estimating the full potential water use of the vineyard, then modifying it by using a deficit irrigation level (RDI%). Full potential water use by the vineyard varies as a result of climatic conditions and the size of the canopy. The climate factor can be estimated using reference evapotranspiration (ET_o) values, which indicate variable vine water use over the course of the season. Water use is also influenced by vine canopy growth from bud break to full canopy expansion. Canopy growth is accounted for by a modifying factor of the ET_o called the crop coefficient (K_c). The crop coefficient increases from a small value after bud break to a larger value as the vine canopy expands to maximum size. Together, these factors ($ET_o \times K_c$) define a water use pattern that begins at a low rate in spring, peaks in mid-summer, and declines as leaf drop approaches:

Vine water use for a specific level of deficit irrigation = $ET_o \times K_c \times$ RDI%, where ET_o is the reference evapotranspiration for a given geographic area, K_c is a crop coefficient, and RDI% is the regulated deficit irrigation level.

Estimating water requirements

Reference ET (ET_o) information is available from a network of nearly 100 California Irrigation Management System (CIMIS) weather stations that provide daily reference evapotranspiration values. Two good web-based sources are the UC Statewide IPM 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 values for ET_o for selected Central Valley locations.

The crop coefficient (K_c) is used with reference evapotranspiration values (ET_o) to estimate full grapevine water

Table 3. **Historical (10-year average) reference evapotranspiration ET_o (in/day) for selected California Central Valley locations, CIMIS stations, and ET_o zones**

	Lodi	**Esparto**	**Hanford**
Station No.	166	39	196
ET_o Zone	12	14	16
Jan	0.025	0.031	0.032
Feb	0.053	0.064	0.060
Mar	0.106	0.115	0.109
Apr	0.172	0.172	0.182
May	0.212	0.218	0.222
Jun	0.250	0.254	0.271
Jul	0.254	0.260	0.274
Aug	0.221	0.224	0.241
Sep	0.170	0.168	0.193
Oct	0.106	0.110	0.137
Nov	0.051	0.055	0.068
Dec	0.025	0.029	0.037

use (ET_c) in a non-water-stressed vineyard. K_c values have been experimentally linked to the percentage of shaded area measured on the vineyard floor at midday. They can be measured at any time of the season, but when using the stress threshold RDI method, it is necessary to measure only at the threshold or beginning of the irrigation season. At that time, canopy expansion is essentially complete. The canopy should be measured again if growth continues or canopy reductions occurs, such as due to hedging or leaf removal.

Williams and Ayars (2005), using a weighing lysimeter, demonstrated that vineyard water use and K_c increase linearly with the percentage of land surface shaded by the crop. They suggest measuring the percentage shaded at midday and using the following simplified equation to determine the K_c:

$$K_c = 1.7 \times (\text{percentage of shaded area} \div 100)$$

For example, consider a vineyard with 11-foot row spacing and 7-foot vine spacing. The average amount of shade between two vines is measured at 31 square feet. Comparing that amount with the single-vine area of 77 square feet (7 × 11) yields a 40% shaded area. The K_c is calculated as follows:

$$K_c = (1.7 \times 0.40) = 0.68$$

Calculating full potential water use with historical average ET_o

The best way to illustrate how to calculate the amount of water to apply under deficit irrigation is to select a vineyard with specific site conditions and perform the calculations using a spreadsheet or table. The irrigation scheduling worksheets in tables 4 and 5 illustrate each step in calculating deficit irrigation. The first step is to calculate full potential water use of the vineyard. Specific vineyard conditions in the above example are as follows:

Variety: Cabernet Sauvignon, mature vines.

Spacing: 7 × 11 feet bilateral cordon.

Irrigation application rate: 1 gal/hr emitter, one emitter per vine = 0.021 in/hr application rate.

Vine water status: Leaf water potential threshold of –13 bars reached July 8.

Table 4. Irrigation scheduling worksheet to determine full potential water use, Lodi, California

Date (period)	A = Historical ET_o* (in/period)	B = Crop coefficient† (K_c)	C = A × B Full potential water use (in)
July 8–14	1.82	0.68	1.24
July 15–21	1.72	0.68	1.17
July 22–28	1.69	0.68	1.15
July 29–Aug 4	1.68	0.68	1.14
Aug 5–11	1.63	0.68	1.11
Aug 12–18	1.56	0.68	1.06
Aug 19–25	1.49	0.68	1.02
Aug 26–Sept 1	1.45	0.68	0.98
Sept 2–8	1.37	0.68	0.93
Sept 9–15	1.23	0.68	0.83
Sept 16–22	1.17	0.68	0.80
Sept 23–29	1.05	0.68	0.72
Sept 30–Oct 6	0.97	0.68	0.66
Oct 7–13	0.88	0.68	0.60
Oct 14–20	0.78	0.68	0.53
Oct 21–27	0.66	0.68	0.45
Oct 28–Nov 3	0.54	0.68	0.37
Total			14.75

Assumptions: Leaf water potential threshold was reached July 8; harvest date October 1.

Notes:

*The data at the CIMIS Web site, http://www.cimis.water.ca.gov/cimis or http://ucipm.ucdavis.edu/ ET_o, are the averages of daily data from 1984 to 2003 from the Lodi (CIMIS #42) and West Lodi (#166) weather stations, available at the UCCE San Joaquin County Web site, http://cesanjoaquin.ucdavis.edu.

†Crop coefficient was calculated based on 40 percent midday land surface shaded.

Land surface shaded area: 40%.

K_c = 0.68 = (1.7 × 0.40).

Area: Lodi, CA, CIMIS station #166.

Harvest date: October 1.

Table 4 shows a sample calculation of weekly full potential water use for Lodi, California, using the 1984 to 2003 historical average ET_o for CIMIS stations #42 and #166. After the –13 bar threshold was achieved (July 8 in this example), the net irrigation

Table 5. Irrigation scheduling worksheet using deficit irrigation, Lodi, CA

Date (period)	**C = A × B Full potential water use (in)**	**D = RDI coefficient* (RDI %)**	**E = C ÷ D Net irrigation requirement (in)**
July 8–14	1.24	0.5	0.62
July 15–21	1.17	0.5	0.58
July 22–28	1.15	0.5	0.58
July 29–Aug 4	1.14	0.5	0.57
Aug 5–11	1.11	0.5	0.55
Aug 12–18	1.06	0.5	0.53
Aug 19–25	1.02	0.5	0.51
Aug 26–Sept 1?Sept? 1	0.98	0.5	0.49
Sept 2–8	0.93	0.5	0.47
Sept 9–15	0.83	0.5	0.42
Sept 16–22	0.80	0.5	0.40
Sept 23–29	0.72	0.5	0.36
Sept 30–Oct 6	0.66	1	0.66
Oct 7–13	0.60	1	0.60
Oct 14–20	0.53	1	0.53
Oct 21–27	0.45	1	0.45
Oct 28–Nov 3	0.37	1	0.37
Total	14.75		8.68

Assumptions: Leaf water potential threshold was reached July 8; harvest date, October 1.

Note: *Regulated deficit irrigation level is 50% (0.5)

requirement can be calculated in weekly increments from the threshold date to the end of the season using average historical ET_o values. The K_c used is 0.68 for a 40% midday shaded area. Calculations are made only after the threshold midday leaf water potential (–13 bars) was measured in the vineyard on July 8. The product of ET_o and K_c yields the full potential water use:

$$ET_o \times K_c = \text{Full potential water use } (ET_c).$$

Calculating vine water use with regulated deficit percentage (RDI%)

Once the full potential water requirement for the vineyard has been calculated, the regulated deficit percentage (RDI%) can be used to calculate the amount of water the vineyard will use under the RDI selected. In our example, 0.50, or 50%, of full potential water use was selected. As illustrated in table 5, full potential water use times RDI% equals the net amount of water use for the selected RDI%. Notice that the RDI% increases to 1.0, or 100%, after harvest, because full watering is required to encourage root growth, nutrient uptake, and carbohydrate accumulation. An increase in RDI% to near 100% at about 19°Brix is a strategy common with extended-maturity harvests.

After the net irrigation amount is determined, in this case using historical average ET_o data, further adjustments can be made to account for the current season's climate (ET_o), soil water contribution after irrigation begins, and in-season effective rainfall (see Prichard et al. 2010).

Determining the irrigation amount

Once the crop water requirement has been determined, the irrigator must account for losses such as evaporation, runoff, and 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 loss, 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

Table 6. Practical potential irrigation efficiency (percent) of irrigation systems

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

Source: Hanson et al. 1999.

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

and ensure that even the driest parts of the vineyard receive the net irrigation amount, divide it by the system irrigation efficiency factor (table 6). Examples for furrow and drip systems follow.

Irrigation amount: Furrow irrigation

For example, to supply 2.5 inches of water to a furrow-irrigated field would require 2.5 ÷ 0.75 = 3.3 inches 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, to supply 0.58 inches of water to a drip-irrigated field would require that 0.58 ÷ 0.90 = 0.64 inches of water be applied. Since in our example vineyard the drip system is operated with no runoff, no deep percolation losses, and evaporation at minimum, the distribution uniformity nearly equals the irrigation efficiency. In this case, the net irrigation can be divided by the measured system distribution uniformity to obtain a field specific gross irrigation volume (Hanson et al. 1999).

Determining the irrigation application time (duration)

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 3.3 inches for 30 days in July-August and a 20-acre field with a water supply of 1,200 gallons per minute, the time would be

$$\begin{aligned} T &= (20 \times 3.3) \div 2.67\text{cfs} \\ &= 24.7 \text{ hr.} \end{aligned}$$

Once the irrigation amount and the 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 a relatively small amount of water (such as the 3.3 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 inflow volumes and cutoff times discussed below can minimize overapplication of water.

Irrigation application time: Sprinkler and drip irrigation

To determine the irrigation time,

$$T = D \div AR,$$

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

Using our example for the second week in July, the applied water is 0.64 inches, and the application rate is 0.021 inch per hour. The duration would be

$$\begin{aligned} T &= 0.64 \div 0.021 \\ &= 30.5 \text{ hr.} \end{aligned}$$

Verifying the calculations and applications

The climate-based method described above for determining crop water needs gives an estimate of demand that should be verified and fine-tuned by soil-based monitoring of actual soil water status and or plant water status. Many devices can monitor soil moisture content and soil tension (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 soil water content increases or tension is reduced progressively after each irrigation, too much water is being applied.

Plant water status can be measured using a pressure chamber to assess the adequacy of an irrigation schedule. The plant water status should be measured just prior to irrigation to determine the maximum stress level between irrigations. If the water level climbs past the desired levels or if water stress is reduced, causing new shoot growth, the schedule needs to be adjusted. For detailed information on when to begin irrigation and how to measure water deficits, see Prichard et al. 2010.

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 by 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 or check. Decreasing the cutoff time water (shortening 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 flow into the cracks results in a very high initial infiltration rate, and after the cracks close, infiltration rates become very small. 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 6 illustrates inflow and outflow rates in

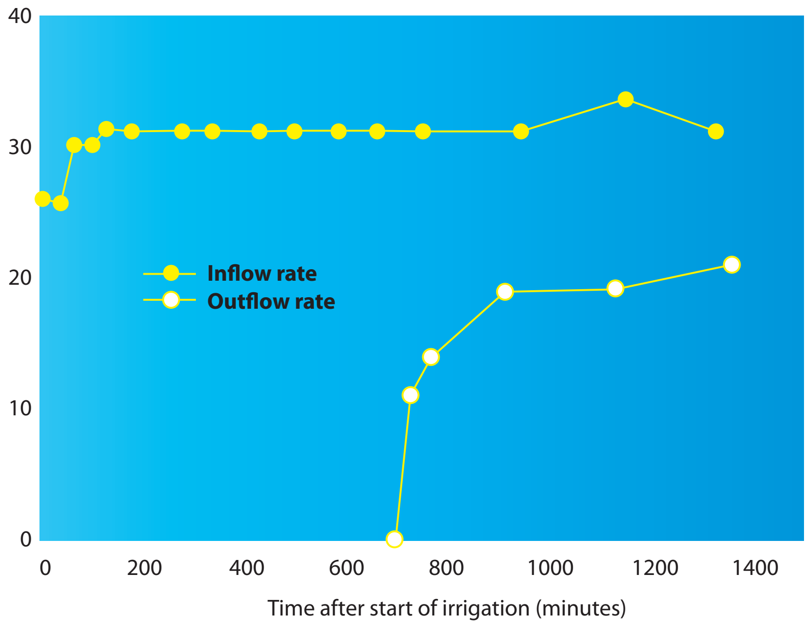

Figure 6. Furrow irrigation inflow and outflow rates (gpm) over the term of irrigation. After Hanson and Schwankl 1985.

a field under furrow irrigation. Note that water must be applied furrow for 700 minutes before it advances to the tail 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. A shorter cutoff time would reduce the 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 the runoff volume.

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

Capturing and recycling runoff 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 vineyard's water requirement while eliminating surface runoff. Uniformity is designed into pressurized irrigation systems, and management should ensure efficiency and elimination of runoff losses by turning the system off before runoff occurs. In a vineyard planted on sloping land, a small amount of runoff tends to accumulate from each emitter or sprinkler, potentially causing offsite movement. Improving the uniformity of water application can avoid runoff. 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 that have poor infiltration or on 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, 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.

Water infiltration can be improved by increasing 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 those with a predominance of clay (platelike 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 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 infiltration rates, at least initially.

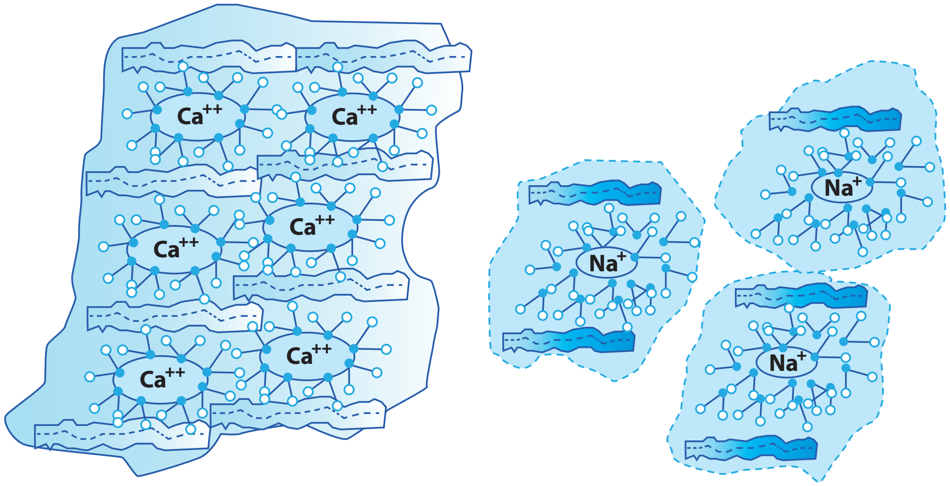

Figure 7. Soil aggregate stability: stable aggregates with plentiful calcium (Ca) on clay exchange sites (left), compared with weak soil aggregates due to low salinity and/or excessive sodium (Na) in the soil pore water (right).

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. 7). 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 categorized 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 in the head of a 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. 8). Structural crusts are a far more common cause of poor water infiltration in California vineyards than are depositional crusts.

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 has very low salinity, such as water from irrigation

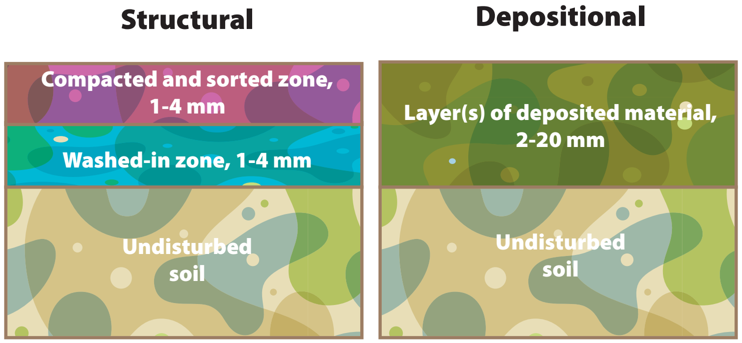

Figure 8. Structural versus depositional crusts.

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. Also, the increased use of herbicides for no-till management can decrease soil organic matter and soil microbial activity, which decreases soil aggregation and reduces pore size.

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 (EC_e).

Sodicity

The index for sodicity is the sodium adsorption ratio (SAR), which depends on the relative sodium, calcium, and magnesium content of the irrigation water. The SAR of a soil sample can be used to estimate exchangeable sodium levels in the soil. With increased levels of exchangeable sodium, the affinity of soil particles for water increases and aggregate stability decreases, effectively 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 water must be taken 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 SAR decreases (table 7). As a general guideline, the SAR should be less than 5 times the EC (figure 9). 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 7. Potential for poor water infiltration

SAR[*]	**Problem likely ECe[†] or ECw[‡] (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).

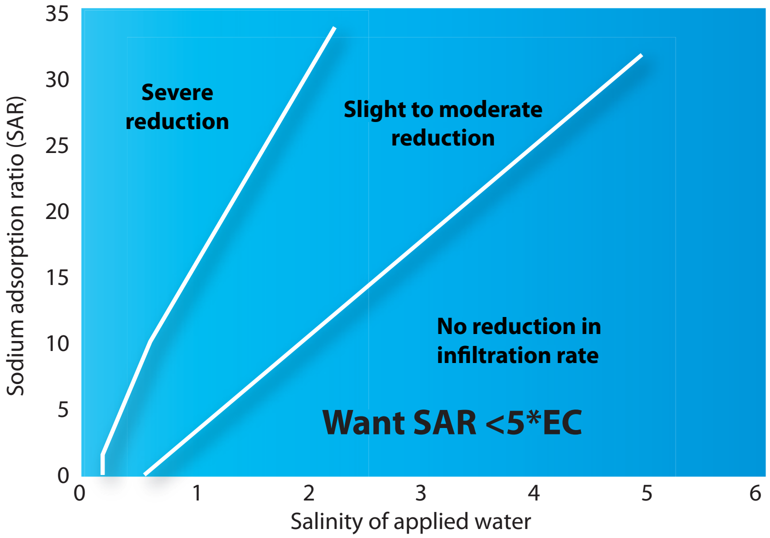

Figure 9. Interaction of total salinity as ECw with the sodium adsorption ratio of irrigation water that can cause infiltration problems.

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 concentrates 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 (a 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 using chemical amendments.

Tillage

Shallow tillage can disrupt structural and depositional crusts. Where crusting reduces infiltration rates, a single tillage can restore infiltration rates; tillage before each irrigation is common in soils with severely reduced infiltration. Shallow tillage using shallow disking or harrowing can break up a surface crust, and shallow tillage to incorporate a pesticide after application can effectively reduce the residues available for offsite transport. Some vineyards have been planted to nonuniform layered soils without deep tillage prior to planting; examination of backhoe pits in such a vineyard reveals significant hardpan and other layers that limit root development. Tillage of vineyard middles is limited to a single pass, with the depth related to the power required and traction of the tractor.

Ripping damages existing roots, especially in vineyards where water infiltration has limited the root zone depth. However, the improved soil characteristics and root pruning from ripping can encourage new root growth. Roots take time to begin growing, and regrowth varies with the season and the carbohydrate status of the vine. In any event, do not till all the middles at once: ripping alternate middles each year produces the best results. Ripping should be most effective in the fall, after harvest when vine water use is low and soils are dry and easy to shatter and mix.

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 the 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.

Figure 10. A mowed cover crop between vine rows. Photo by T. L. Prichard

Crop residues. Vine leaves and prunings, shredded or incorporated into the soil, can be left to decompose, adding organic matter and a certain amount of nutrients to the soil.

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 the limited nitrogen requirement of modern vineyards and limited availability of manures.

Cover crops. Cover crops can help protect the soil surface from droplet impact in winter rainfall or sprinkler irrigation 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. Winter annual cover crops are most often planted in vineyards because they grow during the wet season, reducing the competition for water and nutrients that is a disadvantage of perennial or summer annual covers. They are sown or allowed to reseed in the fall and mowed (fig. 10) or disked in the spring. A winter annual cover crop planted in the fall, grown during the winter and early spring, and mowed or disked at budbreak can produce as much as 3 tons of dry matter (above and below ground) per planted acre. For a comprehensive review of this topic, see Ingels et al. 1998.

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. A 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 a 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 is ($CaSO_4$), 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 or broadcast onto the soil surface. 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.

Table 8. Amounts of amendments required for calcareous soils 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	CaSO4·2H2O, 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 equal weight basis.

[†] Combined acidification potential from S and oxidation of N source to NO3 to release free Ca from soil lime. Requires moist, biologically active soil.

[‡] Acidification potential from oxidation of N source to NO3 only.

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 8 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 supplies 1 meq/L of 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 dormant season.

An alternative to treating water with calcium materials is broadcasting amendments such as gypsum on the soil surface and irrigating it into the soil. The primary advantage of this approach is that it is often less expensive than treating water. Surface application must be properly timed. If infiltration is poor in the summer months, apply the amendment at the onset of those months, not in the preceding fall or winter. If the application is made too early, the amendment will percolate with postharvest irrigations and winter rainfall to depths below where the crust forms. Surface applications are most effective when gypsum is applied prior to the onset of irrigation at rates equivalent to 1 to 2 tons of gypsum per acre. Apply finely and consistently ground gypsum products. Applications that are limited to the berm have been successful at decreased field rates (the same rate per unit area but applied to the berm only) when using drip irrigation. For maximum effect on surface crusting, do not till the soil after gypsum is applied.

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 8 indicates that it takes 133 pounds of 100% pure sulfuric acid per acre-foot of water to release 1 meq/L 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. The primary soil-conditioning 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 these materials to conclude that they are uniformly effective.

Organic polymers, mainly water-soluble polyacrylamides (PAM) and polysaccharides, can 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 decreases 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, Hanson et al. 2010). 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.

Surfactants, or wetting agents, are amendments that reduce the surface tension of water and improve infiltration in hydrophobic soils, which are forest soils high in organic matter. They are not effective in agricultural soils. Other soil-conditioning amendments include synthetic and natural soil enzymes, along with microbial soups. Although there is a long history of soil conditioner development and testing, not enough data exists on the materials to conclude that they are uniformly effective.

Capturing and Filtering Surface Water and Sediments

Reducing the volume or velocity of runoff water can reduce offsite movement of pesticide residues in solution or attached to sediment. Some methods of capturing and filtering surface water and sediment are temporary and are used in a new vineyard or in emergency situations where the need for runoff control is short lived; other methods are permanent. Steep, hillside vineyards should have several types of permanent erosion control measures in place, such as permanent cover crops, adequately sized filter strips between the vineyard and waterways, vegetation at the tail of the field or in the drainage ditch, and permanent sediment basins for collecting or recycling runoff.

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. 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 produce 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. Temporary measures for storing runoff include the following (permanent measures are discussed in separate sections, below). For more information, see Schwankl et al. 2007b.

- **Filter fabric fencing**. A barrier of filter cloth and woven wire stretched between temporary fence posts across a slope can reduce soil movement. Make sure the posts are on the downslope side of the fencing.
- **Straw bale check dam**. To construct a check dam, place bales of clean straw bound with wire or plastic twine across an area of surface sheet flow or gully erosion. Anchor them into the soil surface with rebar or stakes.
- **Straw bale water bar**. Use straw bales to create a temporary water bar across a road or a temporary sediment barrier. A series of straw bale water bars may be needed for long slopes.
- **Straw wattles**. Straw wattles or fiber rolls can slow runoff, reducing erosion and filtering and trapping sediment before the runoff gets into watercourses. Straw wattles must be installed on the contour.
- **Temporary drainage structures**. Constructed at the tail of a field, temporary drainage structures can slow and trap runoff for short periods of time; the water eventually infiltrates the soil (fig. 11). **Temporary sediment basins**. Temporary sediment basins can catch and settle out sediment before it can enter a waterway. They are usually placed at the base of a slope or drainage area. A small basin can be created from compacted soil and rocks or straw bales. The embankment should not exceed 4 feet in height, and a drain or outlet should restrict flow from the basin to allow sediment to be trapped.

Permanent sediment basins

A sediment basin or trap consists of an embankment, an emergency spillway, and a release riser made of perforated pipe (fig. 12). The basin may be located at the bottom of a slope where drainage enters a swale or waterway. 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 and compaction for the berm and correct sizing and construction for water release structures and spillways. If runoff volumes are small, basins can effectively reduce offsite movement of sediment containing adsorbed pesticide residues. If runoff is high enough to cause low retention times, sediment removal efficiency declines rapidly.

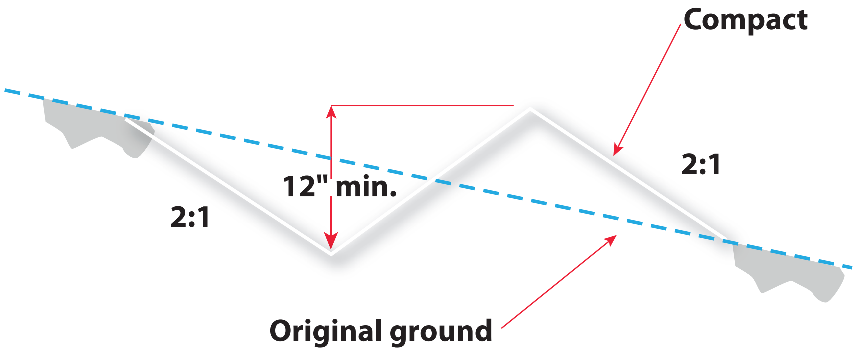

Figure 11. Temporary drainage structure.

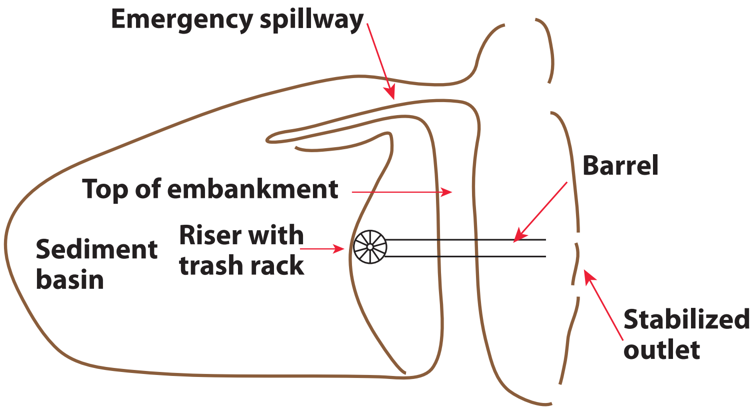

Figure 12. Sediment basin with spillway and release structure.

Effectiveness in removing pesticide residues

Long, Hanson 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. Long, Fulton et al. (2010) suggest various sizes of settling basins based on Stokes' Law. Clay particles carry the bulk of the adsorbed pesticide residues. A settling basin of 57 acre feet would be required in order to provide enough time to settle these small particles out of tailwater runoff inflow at 50 gallons per minute.

A study was conducted in the Central Valley to measure pyrethroid removal by a tailwater recovery pond (Markle 2009). The 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 19 feet by 16 feet by 7 feet deep. About 15% of the irrigation inflow 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 clay particles, which 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.

Permanent cover crops

Cover crops may be grown in vineyard middles, with the rows kept free of vegetation. Plant species used for cover crops may be annuals (planted, grown, and removed each season) or perennials, which generally live 3 or more years. Annual cover crops can be composed of species that reseed themselves naturally each year (for example, annual clovers and medics) or species that are generally removed before they form seeds and must be replanted each year. Perennials such as ryegrass, orchard grass, and fescues are not often used because they compete with the vines for water and nutrients during the summer.

Cover crops can help reduce offsite movement of waterborne pesticide residues in several ways. By shielding the soil from the impact of rain droplets, a winter-grown cover crop can help reduce the likelihood that soil particles will be eroded from the soil surface. Cover crop vegetation may also help slow sedimentation by directly "filtering" soil particles out of moving water and by slowing the speed of water moving over the soil surface. As the weather warms in late winter and spring, cover crops can help deplete excessive soil moisture and increase water storage potential, reducing runoff from storm events at this time of year. For more information, see Ingels et al. 1998 and O'Geen et al. 2006a and 2006b.

Early-fall establishment of cover crops is critical to their effectiveness in capturing runoff water and sediments containing pesticide residues. Among the best cover crops are perennial sods, which have dense foliage and root systems. Reseeding winter annual grasses such as Blando brome or Zorro fescue work well after establishment (Ingels et al. 1998). Cover crops are often mentioned as helping reduce the runoff of pesticide residues; however, research measuring such reductions is limited or nonexistent. However, numerous studies have shown that cover crops can reduce runoff volume and sediment. For example, in one Central Coast vineyard, Trios 102 triticale and Merced rye cover crops planted in vineyard middles reduced runoff volume from 46 to 78%, respectively, compared with bare soil (Smith et al. 2008). The comparisons, made over a 3-year period, also found a significant reduction in suspended sediment and turbidity.

Vegetative filter strips

A vegetative filter strip is an area of dense grass or other vegetation, natural or planted, between a vineyard 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, increasing proportionally with the increase in slope up to 50 feet wide for 10% slopes. Filter strips can also reduce sediment flow between vineyard blocks.

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 nonsoluble 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 vegetated strip. Long, Hanson et al. (2010) 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 mixture of perennial ryegrass and tall fescue 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 the vegetative filter strip is used once per irrigation, not for successive sets as would a vegetated ditch.

Vegetated drain ditches

Drainage ditches can be planted with species that help capture sediments and other sediment-absorbed pollutants, and they can also provide for some water infiltration (fig. 13). The most common type of a vegetated drain ditch is a V-shaped channel 2 to 3 feet deep and 4 feet wide at the top. Short, sturdy, hardy perennial grasses such as dwarf fescue and perennial ryegrass are preferred,

Figure 13. Vegetated drainage ditch. Photo courtesy UC ANR.

since once established they withstand the force of runoff water and summer drought conditions. Vegetation in the ditches 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.

Effectiveness in removing pesticide residues

Anderson et al. (2008) found that a vegetated 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 vegetated ditches in Yolo County, California. They described some reduction in diazinon runoff using a V-shaped vegetated ditch, but significant concentrations of diazinon remained in the system outflow after 5 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 vegetated ditch, although the outflow water was still at 33 times the water quality standard of 15 parts per trillion. Anderson et al. (2008) found an average 35% reduction of chlorpyrifos concentration in runoff water 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 vegetated 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 vegetated ditch. Additionally, Gill et al. (2008) found a 25% reduction of pyrethroid (lambda-cyhalothrin) residues after moving runoff water through a vegetated ditch.

Tailwater Collection and Recycling

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

Tailwater collection systems have most frequently been used in row and field crops and are not as common in surface-irrigated tree and vine crops. However, there is no reason tailwater collection and recycling systems cannot be used in permanent crops using furrow or border-check irrigation. Their use is an excellent way to improve irrigation efficiency and minimize tailwater runoff impacts.

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

Advantages and disadvantages of a tailwater return system

Advantages

- Minimizes risk of 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 share 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

Tailwater return systems can be managed in many ways, 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 check, in a tailwater ditch, 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 also underway to develop enzymes to treat pyrethroid residues.

Polyacrylamide (PAM)

PAM effectively reduces pesticide residues attached to soil particles (generally, pyrethroids) that leave the field or are generated in a tailwater ditch 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, Fulton et al. 2010). Table 9 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 20 acres per set. Granular PAM was injected into the irrigation water until the 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.

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

Table 9. **Cost comparisons for selected single-irrigation PAM 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 hours
liquid PAM injected into irrigation water	$32.31	Target concentration = 5 ppm injection time = 12 hr
liquid PAM injected into irrigation water	$12.93	Target concentration = 2 ppm injection time = 12 hr

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

Notes:

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

†Injection time = time needed for water advance to end of furrows.

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, Hanson et al. 2010). 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 near 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 from furrow-irrigated fields when applied to 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 that decreases sediment loss is increased infiltration of irrigation water into the field, because PAM effectively reduces the runoff volume (Trout et al. 1995). Sojka, applying PAM at the recommended rate of 10 ppm, found increases in infiltration of 15 to 50% compared with untreated controls. In California, Long, Hanson et al. (2010) 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 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 minimal 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 furrows or 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 applied 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 actually 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 that the rate of a correctly managed variable system, due to the lower amount of runoff. A device that senses runoff flow and applies a controlled rate is under development to address these issues.

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 to 1 acre-foot runoff water, the chlorpyrifos concentration declined to 0.4 ppb (Weston and Jackson 2010). At higher enzyme 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 enzyme, the concentration of chlorpyrifos required to kill half the test organisms was 141 ppb; with enzyme, none of 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 an electronic application unit (fig. 14). In multiple trials, Anderson found that samples treated with Landguard OP-A demonstrated no detectable diazinon, and all were nontoxic to *Ceriodaphnia dubia*, another aquatic arthropod test organism.

A RISK ANALYSIS CASE STUDY: VINE MEALYBUG

The management practices presented in this publication have been proven to effectively reduce the offsite movement of pesticide residue in runoff from vineyard operations. The following case study expands on the example introduced in the "Overview of Risk Evaluation," above, and illustrates how specific changes can be made in vineyard operations to reduce pesticide movement from the vineyard. For further information on management options given below, see the discussions in earlier sections of this publication.

Crop: Mature Cabernet Sauvignon vineyard.

Topography: Undulating topography, 0 to 4% slope.

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

Soil: San Joaquin Sandy Loam, prone to soil surface crusting, which limits water infiltration.

Irrigation system: Drip postharvest.

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

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

Proximity to surface water sources: Edge of field drainage ditch contains irrigation runoff from neighboring lands.

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

Pest: Vine mealybug (VMB) *(Planococcus ficus).*

Pest detection: Mid to late-season preharvest.

We begin the risk assessment with Flowchart 1 (see p. 42), considering possible routes by which pesticide could move off the vineyard 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 applications near surface water sources, then review management practices to mitigate the risk.

Irrigation Runoff Risk

Since a postharvest irrigation has been applied, no further irrigation runoff risk exists.

Application Near Surface Water Sources Risk (Drift)

Because the vineyard poses a significant risk due to its location near a ditch that drains to a surface water source, we must consider how to reduce spray drift that could enter the drainage ditch or creek. Go to Flowchart 5 to consider the following drift management options.

Application conditions

- Do not apply pesticides under dead calm or in wind speeds greater than 10 miles per hour (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 often more still 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 bodies 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: larger droplets generally cause less 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%.
- Use a directed spray to minimize contact with soil.
- Check to verify the expected spray deposition pattern.
- Service and calibrate spray equipment regularly.
- Check the system for leaks. Small leaks under pressure can produce very fine droplets. Large leaks contaminate soil, which can be moved offsite by water.
- Use low pressure and a spray volume 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 be necessary to use a different product to reduce the chance of drift.
- Use drift control or drift reduction spray additives or agents. 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 deposition.
- Use spray adjuvants, which can greatly reduce the application volume without compromising pesticide efficacy.
- Use the maximum spray volume per acre and low pressure.
- Treat buffer zones with materials that pose the least risk to aquatic life.

Buffer zones

- Maintain adequate buffer zones around the treated site to ensure that pesticides do not drift onto sensitive areas. Read the label to determine the size of the buffer zone required for the application rate of active ingredient.
- Drift deposits can be reduced 75 to 95% up to 98 feet downwind if setback distances are vegetated with grass or shrubs (Wolf et al. 2003).

Storm Water Runoff Risk

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

In our sample vineyard the pesticide application for vine mealybug occurs after harvest, when there is a risk that residues could be moved offsite by storm water runoff.

Proceeding to Flowchart 4, the first step is to evaluate vineyard IPM practices that control vine mealybug. (For more information, see the UC IPM Grape Pest Management Guidelines, http://www.ipm.ucdavis.edu/PMG.

Integrated Pest Management: Vine mealybug *(Planococcus ficus)*

Vine mealybugs are small (adult females are about ⅛ inch long), soft, oval, flat, distinctly segmented, and covered with a white, mealy wax that extends into spines (filaments along the body margin and the posterior end). The adult male is smaller than the female, has wings, and flies short distances to mate. There are three to seven generations per year.

All or most life stages of the vine mealybug can be present year-round on a vine, depending on the grape-growing region. During the winter months, vine mealybug eggs, crawlers, nymphs, and adults live under the bark, in developing buds, and on roots.

As temperatures warm in spring, vine mealybugs become visible as they move from the roots and trunk to the cordons and canopy. By late spring and summer, vine mealybugs can be found on all parts of the vine: hidden under bark and exposed on trunks, cordons, first- and second-year canes, leaves, clusters, and roots. Ants may transport vine mealybugs from the roots to aboveground plant parts, where they continue to tend the mealybugs throughout the remainder of the growing season.

Damage by the vine mealybug is similar to that of other grape-infesting mealybugs in that it produces honeydew that drops onto the bunches and other vine parts and serves as a substrate for black sooty mold. If ants are not present, a vine with a large population of this pest can have so much honeydew that it resembles candle wax. Also, the mealybug itself can be found infesting bunches, making them unfit for consumption. Like the grape, obscure, and longtailed mealybugs, vine mealybug can transmit grape viruses.

Pest monitoring

Pheromone traps for vine mealybug are available for determining whether an infestation is near or in the vineyard. The lure that is placed inside each trap contains the sex pheromone produced by female vine mealybugs to attract winged adult males. Tent-shaped red traps are recommended because the shape and color tend to reduce the number of nontarget insects that are caught. Place traps in and around the vineyard by April 1 in the southern San Joaquin Valley and by May in areas farther north.

- Choose two trap sites for each 20 to 40 planted acres.
- Put one trap in the center of the block and the other on the edge near a staging area. These traps can attract vine mealybug males from as far away as ¼ mile.
- Attach traps to the trellis wires so they are in the cluster area.
- Label the trap with the block name and row number of its location and the dates it remains in the vineyard.
- Check traps for the presence of male vine mealybug every 2 weeks through November.
- Follow the manufacturer's recommendations for storing and replacing pheromone lures.
- Replace traps if soil particles have covered the sticky inside surface.
- Monitor vineyard for unusual and excessive ant activity.
- Look for water-soaked or "stained" appearance of sap flow on lower trunk or spurs.
- Check first in areas where birds tend to roost or land, such as trees power lines, riparian areas, etc.

Establishing an action threshold

After bloom, pull basal leaves to look for vine mealybug crawlers and honeydew in the canopy; also look under the bark on the trunk and cordons. During bloom and veraison, treatment may be warranted for even a moderate population of nymphs on leaves (mealybugs present in from 10 to 15% of the vineyard), but if possible it is better to wait until postharvest to treat in order to preserve natural enemies. Look for ant activity in vines and along drip lines. Also, the presence of ants moving up and down the vine may indicate the presence of *Pseudococcus* mealybugs or European fruit lecanium scale, as well as vine mealybug,

Vine mealybug produces more honeydew than other mealybugs, and this is particularly noticeable if no ants are present. Thus, when searching for vine mealybug during summer, look for honeydew exudates on the clusters, trunk, and cordons. These exudates resemble melted candle wax if the infestation is severe, and basal leaves appear shiny and sticky. Sooty mold grows on the honeydew, and permanent parts of the vine appear black in fall and winter. Also look for fallen leaves beneath the canopy in July and August. To locate less severe infestations, look for all stages of the insect under the bark, predominately at the graft union, on trunk pruning wounds, and below the base of the spur.

If vine mealybug is found in the vineyard, treatment is recommended. There are two approaches to managing mealybugs: eradication and yearly management. Eradication using chemical applications is most likely to be successful in young vineyards or in vineyards where only a few isolated vines are infested. To increase chances of success in mature vineyards with heavy, loose bark, strip the bark off the trunk and cordons before applying a chemical. Eradication is most probable in areas where no nearby vineyards are infested with vine mealybug. If 2 years of effort do not eliminate vine mealybug from the vineyard, switch to a yearly management program.

Management options

Biological control

Because the parasites that attack *Pseudococcus* mealybugs do not attack the vine mealybug, two potential candidates for natural control have been imported and released in Riverside, Kern, and Fresno Counties. The most successful of these has been *Anagrus pseudococci*. This species has provided up to 20% parasitism in some vineyards in the Coachella Valley and up to 90% parasitism in the San Joaquin Valley. It is extremely important to promote parasites because they are active late in the growing season and can reduce vine mealybug populations before the pest begins to move to the lower part of the trunk in October. To a limited extent, they can parasitize vine mealybug when it is located under the bark where chemicals cannot penetrate. Ants must be controlled to keep them from interfering with these natural enemies. In the coastal regions, a lady beetle called the mealybug destroyer *(Cryptolaemus montrouzieri)* attacks vine mealybug eggs and crawlers.

Cultural control

The female mealybug is unable to fly, so it must be carried by humans, equipment, or birds, or be present on vines at the time of planting. Do not allow contaminated equipment, vines, grapes, or winery waste near uninfested vineyards. Movement of over-the-row equipment or equipment that pushes brush can be a major source of infestations in new locations; steam-sanitize equipment before moving it to uninfested portions of the vineyard. Do not spread infested cluster stems or pomace in the vineyard. To reduce contamination, cover all pomace piles with clear plastic for several weeks and avoid creating piles that consist predominately of stems.

Organically acceptable methods

Biological and cultural controls are organically acceptable management tools. The repeated use of 415 oils during the spring and summer has shown good results in winegrapes. This also helps manage mildew, but the use of sulfur must be avoided. No research studies have yet been done in California on the efficacy of oils or calcium polysulfide in controlling vine mealybug, but these materials have not proven to be effective in controlling the grape mealybug.

Chemical control

If vine mealybug is discovered in the vineyard in late summer or fall, apply a foliar insecticide immediately after harvest if possible (before the nymphs begin to move to the lower parts of the trunk) to kill mealybugs on the leaves and wood so that the infestation does not spread to other parts of the vineyard when leaves drop or when the vines are pruned. If preharvest interval restrictions permit, apply methomyl or dimethoate to infested vines. Take precautions during harvest operations to prevent movement of insects to noninfested vines.

The following year, apply a delayed-dormant treatment of chlorpyrifos or buprofezin, then, in areas with light soils, treat with imidacloprid (soluble formulation) at bloom. Make either a single application of imidacloprid through the drip system or a split one, depending on soil type. During summer, treat with buprofezin. Other materials (methomyl and dimethoate) are available for treating vine mealybug during summer, but they are not as effective and are more disruptive of beneficials. In the north coast, the first application of buprofezin is not recommended until late spring or early summer; imidacloprid is not as effective in controlling pests in heavy clay soils. The UC IPM Program recommends following this program for a maximum of 2 years. If vine mealybug is still present in the vineyard after 2 years, switch to a yearly management program.

Yearly management program

Areas with light-textured soils. In vineyards known to be infested with vine mealybug, make a bloom-time application of imidacloprid either as a single application or a split application through the drip line. The following year, treat either with chlorpyrifos in the delayed-dormant period or with buprofezin in the delayed-dormant period and again in the summer. Alternating insecticides each year helps prevent the development of insect resistance.

Areas with heavy clay soils. In vineyards known to be infested with vine mealybug, make an application of buprofezin or methomyl as soon as crawlers are present on the leaves (in late spring to early summer); a second application can be made no sooner than 14 days later. (For table grapes, an application can be made earlier than late spring.) Apply a foliar insecticide immediately after harvest to kill mealybugs before the nymphs begin to move to the lower parts of the trunk in late October.

Selecting Pesticides to Reduce Water Quality Risks

Continuing to work our way through Flowchart 4, the next step is to select pesticides for the first and subsequent treatments.

Treatment options (table 10) are derived from the UC IPM Grape Pest Management Guidelines, http://www.ipm.ucdavis.edu/PMG/, combined with the potential for runoff risk and overall risk from table 2. Table 10 includes two organophosphates and one carbamate for treating vine mealybug.

Many organophosphates are highly soluble in water and are subject to runoff risk; pyrethroids are highly hydrophobic and adsorb readily to soil sediments, making them also subject to offsite movement.

Since vine mealybug was first discovered in late summer in our sample orchard, apply a postharvest treatment of a foliar insecticide (chlorpyrifos, methomyl, or dimethoate) to kill mealybugs on the

Table 10. Common treatment options for vine mealybug for conventional winegrape production

Chemical	Trade name	Chemical class	Solution runoff potential*	Adsorption runoff potential†	Overall runoff risk‡
chlorpyrifos	Lorsban	organophosphate	high	intermediate	very high
dimethoate	Dimethoate	organophosphate	low	low	low
methomyl	Lannate	carbamate	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.

leaves and wood so that the infestation does not spread to other parts of the vineyard when leaves drop or when the vines are pruned. Postharvest treatments are recommended only for the first season that vine mealybug is discovered.

A postharvest or a delayed-dormant pesticide application is at risk of causing offsite movement of pesticide residue in storm water runoff. Selection of the material to use should be based on efficacy, potential persistence in solution and adsorbed runoff, and the toxicity in water. The materials recommended for a late-season application are organophosphate or carbamate insecticides. However, these materials differ in their potential for pesticide runoff. Dimethoate and methomyl have much lower solution aquatic toxicity and less persistence in the environment than does chlorpyrifos. Both have good efficacy, but dimethoate has the lowest runoff risk overall.

Mixing and Loading Pesticides Near Surface Water

The next consideration in Flowchart 4 for managing vine mealybug is to consider pesticide mixing and loading practices and their impact on surface water quality.

The mixing and loading site in our vineyard is within 50 feet of a surface water ditch. Mixing and loading practices include filling the tank to the proper level without overfilling, triple-rinsing containers and adding the rinsate to the tank, and rinsing the tank and applying the rinsate to the field. Installing a concrete pad with a catchment sump is also a good way to reduce risks from mixing and loading pesticides near surface water sources.

Avoid application during risk-prone times

Management practices to mitigate the risk of offsite movement of pesticides include avoiding application when rain is predicted, especially when soils have been saturated by previous rainfall. It is best to apply organophosphate materials immediately after harvest to avoid the heavy rain season.

Improve water infiltration

Chemical amendments

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

Calcium materials. Adding calcium salts to soil and water increases both 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 equivalent to 1 to 2 tons per acre.

Acids and acid-forming materials. Commonly applied acid or acid-forming amendments include sulfuric acid ($H2SO_4$), 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. The 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 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 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. Organic matter additions aimed at improving or sustaining aggregate stability and water infiltration must be incremental and continual to be effective. There are several ways for growers to achieve this.

Crop residues

Vine leaves and prunings, shredded or incorporated into the soil, can be left to decompose, adding organic matter (and some nutrients) to the soil.

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.

Cover cropping

Cover crops can help protect the soil surface from droplet impact under winter rainfall and can provide significant organic matter biomass for decomposition and microbial stabilization of soil aggregates, in the process increasing infiltration rates. In addition, cover crop residue can slow the velocity of surface water, reducing erosion and subsequent depositional crusting.

Since the soil in the sample vineyard is prone to crusting, growing cover crops during the winter and early spring protects the soil surface from soil dispersion and crusts that limit water infiltration and increase the runoff potential. The increased organic matter from the cover crop also promotes water infiltration.

These practices should be implemented in the previous (or at least the current) season. In our sample vineyard, the soil tends to crust and has some slope, so high-intensity rainfall is likely to cause surface runoff even when the soil is not saturated.

Tillage

Light surface tillage breaks up crusts and can improve water infiltration. Pesticide application after such tillage incorporates residues into the soil, reducing runoff potential.

Runoff water capture

Intercept the movement of surface water

Any reduction in the volume or velocity of runoff can reduce the concentration of soluble and sediment-attached pesticide residues. There are several ways to intercept the offsite movement of surface water and sediment. Some are temporary and are used in a new vineyard or in emergency situations where the need for runoff control is short lived; other methods are permanent. Steep hillside vineyards should have several types of permanent erosion control measures in place, such as permanent cover crops, adequately sized filter strips between the vineyard and any waterways, and permanent sediment basins.

Capture runoff water

Sediment basins can prevent runoff from entering surface water sources only if their capacity is great enough to store the runoff water until it infiltrates. Some growers on high-infiltration soils install a berm around the lower end of the vineyard to trap runoff water until it infiltrates. On sloping soils, temporary structures such as straw wattles can divert and slow runoff water. Vegetative filter strips and ditches can help infiltrate runoff water containing soluble residues.

Treat runoff water

Runoff water containing organophosphate insecticide residues can be treated with the degradation enzyme Landguard OP-A to reduce or eliminate residues before the water exits the farm. This product promotes the breakdown of most organophosphate pesticides into less toxic metabolites. Since no pyrethroid insecticide is recommended for vine mealybug control, sediment reduction measures are not considered.

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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 (ft^2)	0.0929	10.764	square meter (m^2)
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 (m^3)
acre-foot (ac-ft)	1,233	0.000811	cubic meter (m^3)
cubic foot (ft^3)	28.317	0.353	liter (l)
cubic yard (yd^3)	0.765	1.307	cubic meter (m^3)
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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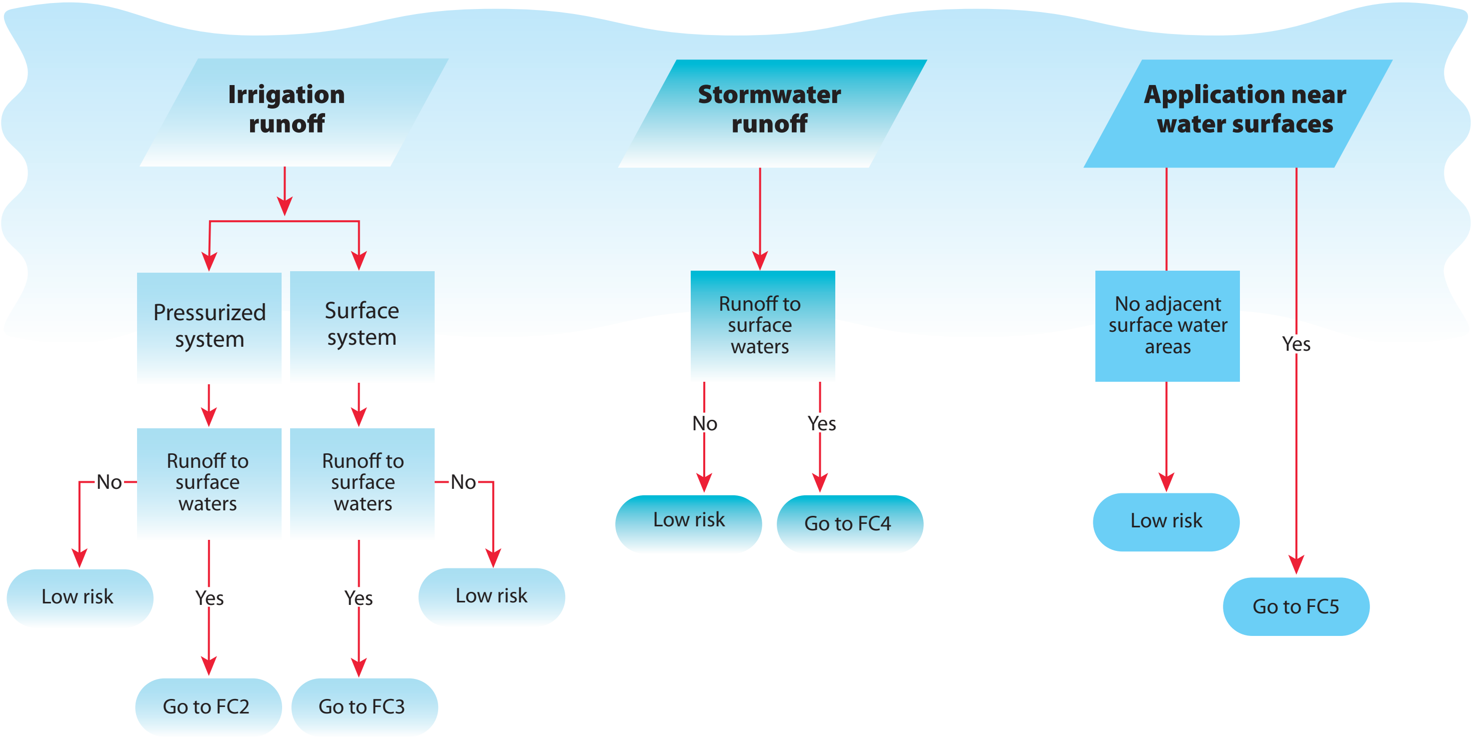
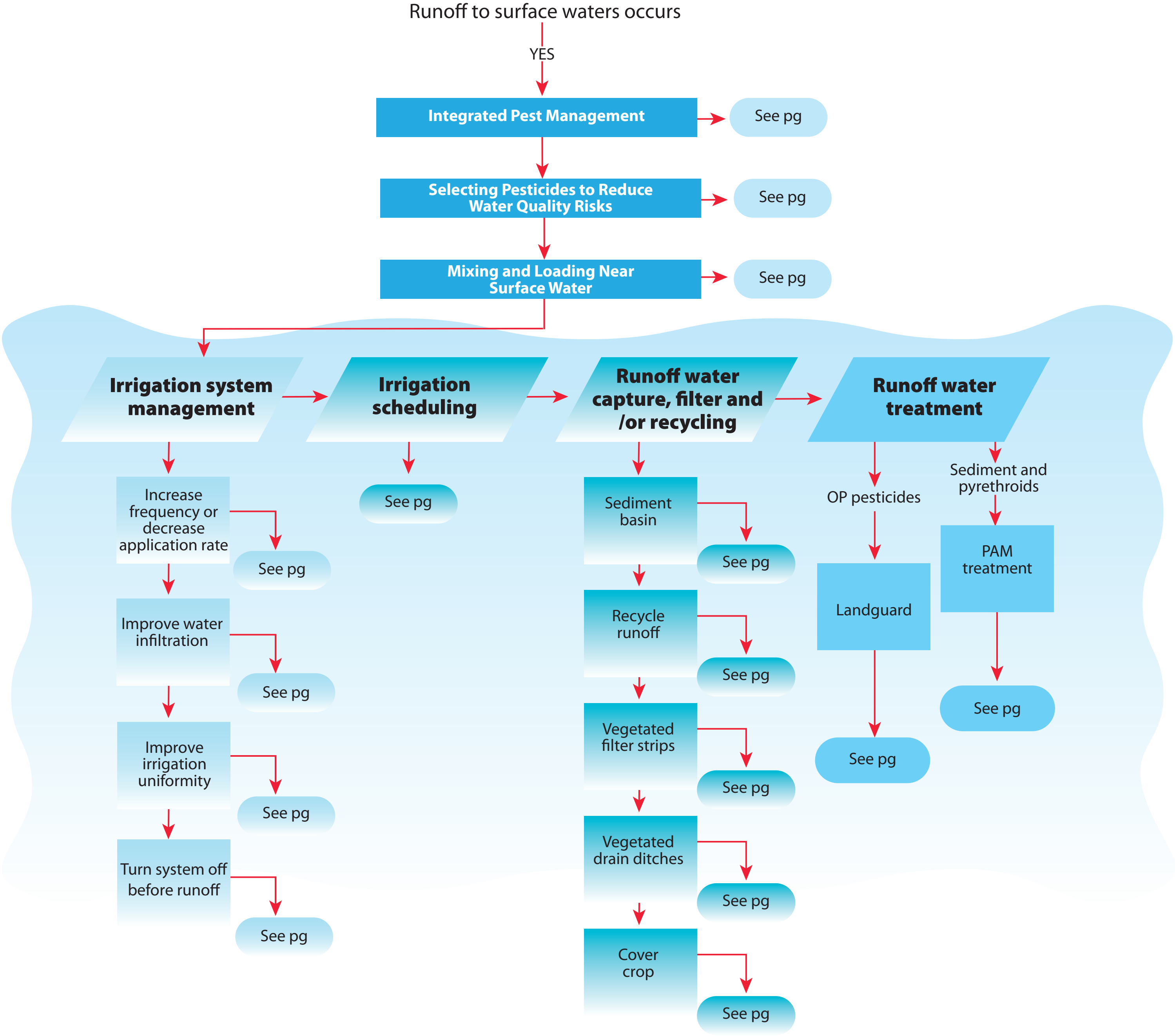
FC1
Assessing the Risk of Offsite Movement of Ag Chemicals to Surface Waters

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

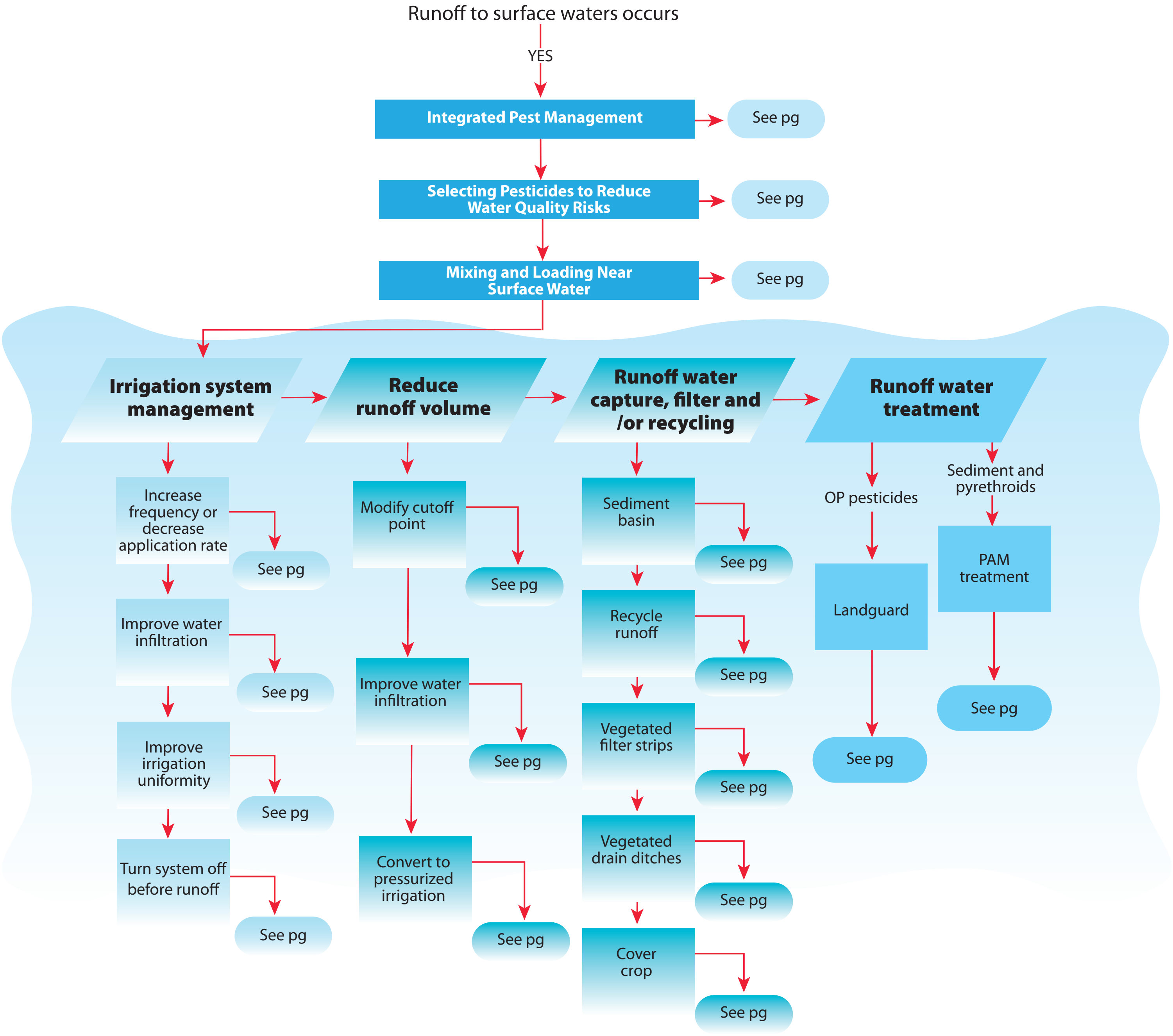


FC2
Reducing the Risk of Offsite Movement of Ag Chemicals in Runoff – Pressurized Irrigation Systems

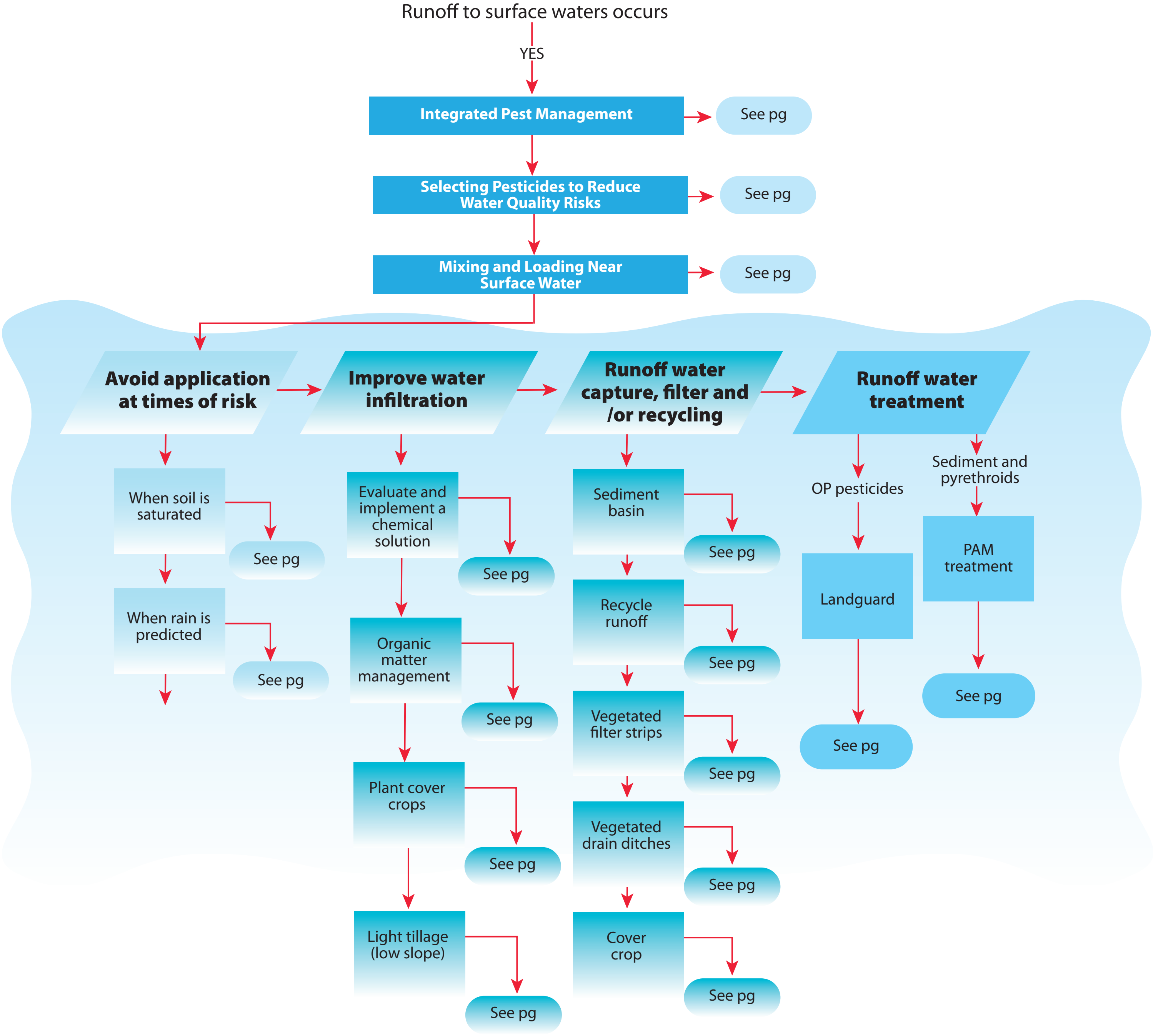


FC3

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



FC5
Reducing the Risk of Offsite Movement of Ag Chemicals Near Water Surfaces in Drift Situations