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Pesticide Choice: Best Management Practice (BMP) for Protecting Surface Water Quality in Agriculture

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Pesticides are one type of pollutant found in California's surface waters at levels that may be harmful to the aquatic ecosystem. When toxicity occurs, pesticide loadings and surface water pesticide concentrations must be reduced to levels that are not harmful to aquatic life. Factors affecting the potential for a pesticide to move "offsite" from a treated area include field soil properties, climate, grower management practices, and the physical and chemical properties of the active ingredient. This publication provides information to assist pesticide users in evaluating their choice of pesticide products on the basis of the potential to impact surface water quality.

PESTICIDE PROPERTIES AFFECTING TRANSPORT IN WATER

The likelihood that a pesticide will move in irrigation or stormwater runoff from the site of application depends in large part on the properties of the active ingredient (a.i.), including the pesticide's field dissipation half-life, adsorption coefficient (K_{oc}), and aqueous solubility. Field dissipation half-life is the time required for half of a given quantity of a formulated pesticide to degrade or dissipate from the soil. In general, pesticides that remain in the field for many weeks after treatment (i.e., half-life >40 days) are more available to move in runoff because they last the longest in the environment.

The K_{oc} is the soil adsorption coefficient for the pesticide, which often depends on the pesticide's hydrophobicity. The larger the K_{oc} value, the more strongly the pesticide adsorbs to soil. K_{oc} determines how a pesticide moves in runoff. A pesticide with a low K_{oc} (i.e., weak adsorption) and high solubility will move in the dissolved form, while a pesticide with high K_{oc} (i.e., strong adsorption) will move primarily by associating itself with eroded soil or sediment particles.

Water solubility is the amount of pesticide that can be dissolved per liter of water. As solubility increases, K_{oc} usually decreases. However, there are exceptions to this general rule. For example, glyphosate (the active ingredient of Roundup) is highly water soluble, but adsorbs strongly to soil and does not move in water.

The K_{oc}, solubility, and half-life values for California-registered insecticides, miticides, fungicides, and herbicides are given in tables 1 through 4. The physicochemical data in these tables were extracted from USDA-ARS 2004 and PesticideWise 2004.

AQUATIC TOXICITY OF PESTICIDES

Pesticides differ in their degree of toxicity to aquatic life. In general, insecticides tend to have high toxicity to fish and invertebrates, while some herbicides have high toxicity to aquatic plants (i.e., phytotoxicity). The standard indicator species that the U.S. Environmental Protection Agency uses to assess water quality include zooplankton

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Table 1. Key pesticide properties influencing the potential for insecticides to move in runoff

Insecticide active ingredient (Common name)	Solubility (mg/L)*	K_{oc}†	Field dissipation half-life (days)‡	Aquatic toxicity§
abamectin	5	5,000	28	high
acephate	818,000	2	6	moderate
azinphosmethyl	28	940	10	very high
bifenthrin	0.0001	237,000	26	very high
carbaryl	110	288	14	moderate
carbofuran	350	46	50	high
chlorpyrifos	1.18	9930	43	extremely high
cyfluthrin	0.02	100,000	22	extremely high
cypermethrin	0.004	61,000	77	very high
diazinon	60	1,520	40	very high
diflubenzuron	0.08	8,700	10	very low
dimethoate	39,800	20	7	high
disulfoton	12	600	30	high
endosulfan	0.32	12,400	60	very high
esfenvalerate	0.0002	5,300	42	very high
fenpropathrin	0.014	5,000	14	high
fipronil	2	838	96	very high
imidacloprid	580	440	127	very low
lambda-cyhalothrin	0.005	180,000	30	very high
malathion	130	1,200	9	extremely high
methamidophos	1,000,000	5	6	high
methidathion	220	400	7	very high
methomyl	58,000	72	30	high
methyl parathion	55	6,300	10	very high
naled	2,000	180	1	very high
oxamyl	282,000	25	4	moderate
oxydemeton-me	1,000,000	10	10	moderate
permethrin	0.006	100,000	42	very high
phorate	22	1,000	37	very high
phosmet	20	668	14	very high
profenofos	28	2,000	9	moderate
spinosad	89	16,420	0.4	very low
tebufenozide	0.83	389	348	very low
thiodicarb	19.1	351	5	high
tralomethrin	0.001	100,000	27	very high

Sources: PAN 2004; PesticideWise 2004; USDA-ARS 2004.
Notes:
*Amount of pesticide able to be dissolved in water.
†Adsorption coefficient normalized over soil organic carbon content.
‡Time required for 50% of the chemical to disappear from the soil following treatment.
§Based on toxicity evaluation of water fleas *(Daphnia magna* or *Ceriodaphnia dubia)*, rainbow trout *(Oncorhynchus mykiss)*, or phytoplankton (typically *Selenastrum capricornatum*). See table 5.

Table 2. Key pesticide properties influencing the potential for miticides to move in runoff

Miticide active ingredient (Common name)	Solubility (mg/L)*	K_{oc}†	Field dissipation half-life (days)‡	Aquatic toxicity§
avermectin	5	5,000	28	high
bifenazate	4	4,600	5	moderate
clofentezine	0.0025	45,300	40	high
dicofol	0.8	6,064	57	high
fenbutatin oxide	0.0127	2,721	95	very high
formetanate hydrochloride	820,000	275	9	high
hexythiazox	0.5	6,200	30	moderate
propargite	0.6	41,000	84	high
pyridaben	0.012	110,000	86	very high

Sources: PAN 2004; PesticideWise 2004; USDA-ARS 2004.
Notes:
*Amount of pesticide able to be dissolved in water.
†Adsorption coefficient normalized over soil organic carbon content.
‡Time required for 50% of the chemical to disappear from the soil following treatment.
§Based on toxicity evaluation of water fleas *(Daphnia magna* or *Ceriodaphnia dubia)*, rainbow trout *(Oncorhynchus mykiss)*, or phytoplankton (typically *Selenastrum capricornatum*). See table 5.

(waterfleas, scud), fish, and phytoplankton (green algae) (US EPA 2002). Acute effect levels are typically based on LC_{50} (the dose of a pesticide that kills half the test organisms) or EC_{50} (the dose that causes some sublethal effect in half the test organisms). Aquatic toxicity rankings from extremely low to extremely high were used to determine an appropriate risk category (table 5). Data were extracted from the US EPA AQUIRE database (PAN 2004). When a range of values was given for a specific effect, the lowest concentration was generally selected for the toxicity ranking. The toxicity for the most sensitive indicator species was then used to rank the overall aquatic toxicity. The overall aquatic toxicity rankings for California registered insecticides, miticides, herbicides, and fungicides are listed in the last column in

Table 3. Key pesticide properties influencing the potential for fungicides to move in runoff

Fungicide active ingredient (Common name)	Solubility (mg/L)*	K_{oc}†	Field dissipation half-life (days)‡	Aquatic toxicity§
azoxystrobin	7	1,590	65	very high
captan	5	200	3	low
carboxin	195	260	6	moderate
chlorothalonil	0.6	5,000	30	high
copper sulfate	10,000	30	4	very high
cymoxanil	780	110	5	moderate
cyprodinil	13	1,000	50	moderate
dicloran	7	1,000	10	moderate
dodine	700	100,000	20	high
fenarimol	14	760	360	low
fenbuconazole	38	5,776	247	high
fosetyl-al	120,000	166	1	low
imazalil	1400	4,000	150	moderate
iprodione	14	700	14	moderate
mancozeb	6	6,000	70	high
maneb	6	2,000	70	high
myclobutanil	142	500	66	moderate
propiconazole	110	1,000	110	high
thiabendazole	50	2,500	403	high
thiophanate methyl	3.5	1,830	6	moderate
thiram	30	670	15	very high
triadimefon	72	300	26	moderate
triflumizole	12,500	40	14	high
vinclozolin	1,000	100	20	moderate
ziram	65	400	30	very high

Sources: PAN 2004; PesticideWise 2004; USDA-ARS 2004.
Notes:
*Amount of pesticide able to be dissolved in water.
†Adsorption coefficient normalized over soil organic carbon content.
‡Time required for 50% of the chemical to disappear from the soil following treatment.
§Based on toxicity evaluation of water fleas *(Daphnia magna* or *Ceriodaphnia dubia)*, rainbow trout *(Oncorhynchus mykiss)*, or phytoplankton (typically *Selenastrum capricornatum*). See table 5.

Table 4. Key pesticide properties influencing the potential for herbicides to move in runoff

Herbicide active ingredient (Common name)	Solubility (mg/L)*	K_{oc}†	Field dissipation half-life (days)‡	Aquatic toxicity§
alachlor	240	124	27	very high
atrazine	33	147	173	high
benefin	0.1	9,000	40	high
bensulide	6	1,000	120	high
bentazon sodium	2,300,000	35	27	moderate
bromacil	700	32	60	very high
bromoxynil butyrate	27	1,079	7	high
clethodim	5,400	10	3	low
clopyralid	9,000	36	30	low
cyanazine	155	218	14	very high
cycloate	95	272	27	moderate
2,4-d	890	48	10	moderate
2,4-db (salt)	46	440	5	high
dcpa	0.5	5,600	100	moderate
dicamba (salt)	360,000	2	16	moderate
dichlobenil	21	400	60	high
diclofop	0.8	16,000	20	high
difenzoquat methyl sulfate	817,000	55,000	100	moderate
diquat dibromide	718,000	1,000,000	1000	high
dithiopyr	1	800	400	high
diuron	42	480	90	very high
dsma	254,000	7,000	180	high
endothall	100,000	20	3	high
eptc	344	200	6	high
ethofumesate	50	340	30	moderate
fenoxaprop ethyl	0.9	9,490	12	high
fluazifop-p-butyl	2	5,700	15	high
glufosinate	1,370,000	100	7	moderate
glyphosate	12,000	24,000	47	moderate
halosulfuron	1,630	100	14	low
hexazinone	29,800	54	79	very high
imazapyr	15,000	100	90	very low
ımazethapyr	200,000	10	90	low
isoxaben	1	1,400	100	high
linuron	75	400	60	high
mcpa	5	1,000	25	high
mecoprop	660,000	20	21	moderate
metham sodium	963,000	10	7	high
metolachlor	530	200	90	moderate
metribuzin	1,000	52	47	very high
msma	1,400,000	7,000	180	moderate
napropamide	74	400	70	moderate
nicosulfuron	12,000	30	21	extremely low
norflurazon	28	600	90	very high
oryzalin	2	600	20	high
oxadiazon	0.7	3,200	60	very high
oxyfluorfen	0.1	100,000	30	high
paraquat	620,000	1,000,000	1,000	moderate
pebulate	100	430	8	high
pendimethalin	0.3	5,000	90	very high
prodiamine	0.01	13,000	120	high
prometryn	33	400	60	very high
propyzamide	15	200	60	high
pyrithiobac sodium	730	70	60	very low
pyrazon	400	120	21	high
rimsulfuron	7,300	47	10	very low
sethoxydim	4,700	100	5	high
simazine	6	130	60	high
thiazopyr	2	400	85	moderate
triclopyr (ester)	23	780	46	high
trifluralin	0.3	7,200	60	very high

Sources: PAN 2004; PesticideWise 2004; USDA-ARS 2004.
Notes:
*Amount of pesticide able to be dissolved in water.
†Adsorption coefficient normalized over soil organic carbon content.
‡Time required for 50% of the chemical to disappear from the soil following treatment.
§Based on toxicity evaluation of water fleas *(Daphnia magna* or *Ceriodaphnia dubia)*, rainbow trout *(Oncorhynchus mykiss)*, or phytoplankton (typically *Selenastrum capricornatum*). See table 5.

Table 5. Basis for aquatic toxicity rankings for California-registered pesticides in tables 1 through 4

Aquatic Toxicity (µg/L, ppb)*	Risk ranking
<0.00014	extremely high
<0.14	very high
<14	high
<1400	moderate
<14000	low
<85000	very low
>85000	extremely low

Source: US EPA 2002.
Notes:
*Based on evaluation of water fleas *(Daphnia magna* or *Ceriodaphnia dubia)* toxicity (typically acute LC_{50}, 48-hr test); rainbow trout *(Oncorhynchus mykiss)* toxicity (typically acute LC_{50}, 96-hr test); or effect on population abundance of the phytoplankton *Selenastrum capricornatum* (typically EC_{50}).

tables 1 through 4. It is important to select a pesticide that has a low toxicity to aquatic life, especially when used near waterbodies.

PESTICIDE RUNOFF RISK

For each California-registered pesticide active ingredient examined in this publication, K_{oc}, solubility, and half-life values were used to fit two USDA-NRCS algorithms to determine the pesticide's tendency to move in dissolved form (i.e., solution runoff) or with soil (i.e., adsorption runoff). The potential to move off site, either in solution or with soil, was then categorized into "high" (great potential to move), "intermediate" (moderate potential to move), and "low" (limited potential to move) (tables 6–9). In general, when a pesticide has a relatively long half-life and a large K_{oc} and/or low solubility, the potential for adsorption runoff is high. If a pesticide has a relatively long half-life and a small K_{oc} and/or high solubility, the potential for solution runoff is high. The runoff potential was then considered together with the aquatic toxicity for a given pesticide to estimate its overall runoff risk. Overall runoff risk in this publication is a product of the runoff potential and the aquatic toxicity; this is listed in the last column in tables 6 through 9 for California-registered insecticides, miticides, fungicides, and herbicides. For example, if a pesticide has a high runoff potential but a low aquatic toxicity, the overall runoff risk is low. If a pesticide has a moderate or high runoff potential but very high aquatic toxicity, the overall runoff risk is high or very high. Pesticides labeled "very high" or "high" in tables 6 through 9 should be used with precautions and/or with proper mitigation practices.

Table 6. California-registered insecticides ranked by potential to move in solution or as adsorbed particles and overall pesticide runoff risk

Insecticide active ingredient (Common name)	Trade name=	Solution runoff potential*	Adsorption runoff potential†	Overall runoff risk‡
diazinon	Diazinon	high	high	very high
endosulfan	Thiodan	high	high	very high
phorate	Thimet	high	high	very high
chlorpyrifos	Lorsban, Dursban	high	intermediate	very high
abamectin	Agri-Mec, Zephyr	high	intermediate	high
fipronil	Regent	high	intermediate	high
tralomethrin	Scout X-Tra	high	intermediate	high
bifenthrin	Capture	low	high	high
cypermethrin	Ammo, Mustang	low	high	high
esfenvalerate	Asana	low	high	high
permethrin	Pounce	low	high	high
cyfluthrin	Baythroid	low	intermediate	high
lambda-cyhalothrin	Warrior, Karate	low	intermediate	high
azinphosmethyl	Guthion	intermediate	intermediate	moderate
methyl parathion	Parathion	intermediate	intermediate	moderate
profenofos	Curacron	intermediate	intermediate	moderate
carbaryl	Sevin	intermediate	low	moderate
disulfoton	Disyston	intermediate	low	moderate
malathion	Malathion	intermediate	low	moderate
methomyl	Lannate	intermediate	low	moderate
methidathion	Supracide	intermediate	low	moderate
phosmet	Imidan	intermediate	low	moderate
thiodicarb	Larvin	intermediate	low	moderate
carbofuran	Furadan	low	intermediate	moderate
fenpropathrin	Danitol	low	intermediate	moderate
diflubenzuron	Dimilin	high	intermediate	low
imidacloprid	Provado	high	intermediate	low
tebufenozide	Confirm	high	intermediate	low
spinosad	Success, Tracer	intermediate	intermediate	low
acephate	Orthene	low	low	low
dimethoate	Cygon	low	low	low
methamidophos	Monitor	low	low	low
naled	Dibrom	low	low	low
oxamyl	Vydate	low	low	low
oxydemeton- me	Metasystox-R	low	low	low

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.

OTHER FACTORS AFFECTING PESTICIDE RUNOFF

The occurrence of pesticide runoff also depends heavily on many other factors, including soil properties, crop production practices, irrigation management, rain events, and pesticide application methods and timing. Soils high in clay and organic matter may adsorb pesticides better than

Table 7. California-registered miticides ranked by potential to move in solution or as adsorbed particles and overall pesticide runoff risk

Miticide active ingredient (Common name)	Trade name=	Solution runoff potential*	Adsorption runoff potential†	Overall runoff risk‡
fenbutatin oxide	Vendex	high	high	very high
pyridaben	Pyramite, Nexter	high	high	very high
clofentezine	Apollo	high	high	high
dicofol	Kelthane	high	high	high
formetanate hydrochloride	Carzol	high	high	high
propargite	Comite, Omite	high	high	high
avermectin	Avid, Agri-mek	high	intermediate	high
hexythiazox	Savey	high	intermediate	moderate
bifenazate	Acramite	intermediate	intermediate	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.

Table 8. California-registered fungicides ranked by potential to move in solution or as adsorbed particles and overall pesticide runoff risk

Fungicide active ingredient (Common name)	Trade name=	Solution runoff potential*	Adsorption runoff potential†	Overall runoff risk‡
azoxystrobin	Quadris, Abound	high	high	very high
copper sulfate	copper sulfate	high	high	very high
fenbuconazole	Indar	high	high	high
maneb	Maneb	high	high	high
propiconazole	Break, Orbit, tilt	high	high	high
mancozeb	Dithane	high	high	high
thiabendazole	Mertect	high	high	high
chlorothalonil	Bravo, Echo	high	intermediate	high
thiram	Thiram	intermediate	low	high
ziram	Ziram	intermediate	low	high
cyprodinil	Vangard	high	high	moderate
imazalil	Fungaflor	high	high	moderate
myclobutanil	Rally, Laredo	high	intermediate	moderate
dicloran	Botran	intermediate	intermediate	moderate
thiophanate methyl	Topsin	intermediate	intermediate	moderate
carboxin	Vitavax	intermediate	low	moderate
cymoxanil	Curzate	intermediate	low	moderate
iprodione	Rovral	intermediate	low	moderate
triadimefon	Bayleton	intermediate	low	moderate
triflumizole	Procure	intermediate	low	moderate
vinclozolin	Ronilan	intermediate	low	moderate
fenarimol	Rubigan	high	intermediate	low
captan	Captan	intermediate	low	low
fosetyl-al	Aliette	low	low	low

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.

Table 9. California-registered herbicides ranked by potential to move in solution or as adsorbed particles and overall pesticide runoff risk

Herbicide active ingredient (Common name)	Trade name=	Solution runoff potential*	Adsorption runoff potential†	Overall runoff risk‡
oxadiazon	Ronstar	high	high	very high
pendimethalin	Prowl	high	high	very high
trifluralin	Treflan	high	high	very high
diuron	Karmex, Direx	high	intermediate	very high
norflurazon	Solicam	high	intermediate	very high
prometryn	Caparol	high	intermediate	very high
benefin	Balan	high	high	high
bensulide	Prefar	high	high	high
dsma	DSMA	high	high	high
isoxaben	Gallery	high	high	high
prodiamine	Barricade	high	high	high
dichlobenil	Casoron	high	intermediate	high
diclofop	Hoelon	high	intermediate	high
dithiopyr	Dimension	high	intermediate	high
fenoxaprop ethyl	Acclaim, Whip	high	intermediate	high
fluazifop-p-butyl	Fusilade	high	intermediate	high
linuron	Lorox	high	intermediate	high
mcpa	MCPA	high	intermediate	high
oxyfluorfen	Goal	high	intermediate	high
atrazine	Aatrex	intermediate	intermediate	high
bromacil	Hyvar X	intermediate	intermediate	high
hexazinone	Velpar	intermediate	intermediate	high
alachlor	Lasso	intermediate	low	high
cyanazine	Bladex	intermediate	low	high
metribuzin	Sencor	intermediate	low	high
dcpa	Dacthal	high	high	moderate
difenzoquat methyl sulfate	Avenge	high	high	moderate
msma	MSMA	high	high	moderate
napropamide	Devrinol	high	intermediate	moderate
thiazopyr	Visor	high	intermediate	moderate
bromoxynil, butyrate	Buctril	intermediate	intermediate	moderate
metolachlor	Dual Magnum, Pennant	intermediate	intermediate	moderate
propyzamid	Kerb	intermediate	intermediate	moderate
simazine	Princep	intermediate	intermediate	moderate
triclopyr	Turflon, Garlon, Grandstand	intermediate	intermediate	moderate
2,4-db	Butyrac	intermediate	low	moderate
cycloate	Ro-neet	intermediate	low	moderate
eptc	Eptam	intermediate	low	moderate
ethofumesate	Nortron, Prograss	intermediate	low	moderate
oryzalin	Surflan	intermediate	low	moderate
pebulate	Tillam	intermediate	low	moderate
pyrazon	Pyramin	intermediate	low	moderate
sethoxydim	Poast	intermediate	low	moderate
diquat	Reward, Diquat	low	high	moderate
glyphosate	Roundup	low	high	moderate
paraquat	Gramoxone extra	low	high	moderate
dicamba	Clarity, Banvel	low	low	moderate
imazapyr	Arsenal, Chopper	intermediate	intermediate	low
pyrthiobac sodium	Staple	intermediate	intermediate	low
halosulfuron	Manage, Sandea, Sempra CA	intermediate	low	low
glufosinate	Finale, Rely	intermediate	low	low
rimsulfuron	Matrix	intermediate	low	low
imazethapyr	Pursuit	low	intermediate	low
2,4-d	2,4-D	low	low	low
bentazon sodium	Basagran	low	low	low
clethodim	Prism, Envoy	low	low	low
clopyralid	Stinger, Transline	low	low	low
endothall	Endothall	low	low	low
mecoprop	MCPP	low	low	low
metham sodium	Vapam	low	low	low
nicosulfuron	Accent	low	low	low

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.

sandy soils; however, clay soils can be more prone to pesticide runoff, as they tend to have low water permeability and may allow water to pool on the soil surface. Correct pesticide application rates, accurate equipment calibration, proper application timing, careful handling of pesticides, minimizing drift, establishing buffer zones around waterways, and proper cleanup and disposal of pesticides minimize the potential for runoff problems associated with pesticide use.

To develop effective mitigation practices, pesticide applicators must understand whether a pesticide moves with runoff in solution or as attachment to solids. For instance, although some pesticides (such as pyrethroids) are not likely to move in the dissolved form in runoff water, they can move by attaching to eroded soil particles and can enter surface streams, where they may cause toxicity to sediment organisms. For these pesticides, it is useful to implement practices to reduce sediment transport in irrigation or storm water runoff from pesticide treated areas. One example of an effective management practice is the use of vegetative filter strips, such as grasses or sedges planted along ditches or streams, to help trap sediments. Other examples include tail-water ponds to help slow the flow of water and enable soil particles to settle out, or using polyacrylimide polymers (PAM) to aggregate soil particles, allowing them to precipitate from the water. However, these practices will not be equally effective if used for reducing the runoff of a pesticide moving primarily in solution. Because water movement is the driving force for any pesticide runoff, improving irrigation efficiency and reducing the amount of runoff is essential when applying pesticides that move in solution. Capturing runoff using a tail pond or retention pond allows more time for pesticides to degrade, resulting in reduced pesticide runoff for pesticides moving either in the solution or in the adsorbed phase.

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