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Project Report

Guidelines for the Selection of Appropriate Best Management Practices

Coalition for Urban/Rural Environmental Stewardship
www.curesworks.org

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Summary

In this report, guidelines for selecting BMPs are based on four practices that have been found to be suitable for mitigating contaminants in runoff in the San Joaquin Valley: sediment basins/ponds, constructed wetlands, vegetated ditches/grassed waterways, and polyacrylamide (PAM) applications to irrigation water. The guidelines are initially presented with flow charts that lead growers through the selection process of BMPs appropriate to their farms. Detailed information on those specific BMPs is also provided for reference and further assistance with the selection of appropriate BMPs.

Introduction

The San Joaquin Valley is one of the most productive agricultural regions in the world and this productivity is heavily dependent on irrigated agriculture. An inevitable consequence of irrigated agriculture is the production of return-flows conveyed down gradient in agricultural drains that eventually discharge to surface waters. Agricultural drainage may have poor water quality characteristics and agricultural return-flows are under increasing regulatory scrutiny in California. Individual farmers and agricultural organizations, such as drainage authorities, are in need of tools to manage the environmental impact of agricultural activities.

Best management practice (BMP) is a catch-all term for a wide variety of agricultural practices directed at mitigating the environmental impact of modern farming. BMPs include improvements in pesticide application methods, drip irrigation, and the use of soil amendments to prevent erosion. The term BMP is also applied to engineered structures such as vegetated ditches, sediment catch basins, and constructed wetlands.

Information on BMPs usable in the Central Valley has only recently been developed. While BMPs studies date back to the 1970s, studies focusing on BMPs for reducing the impacts of agricultural pesticides on water quality in California did not become common until the 1990s (note: studies did focus on DDT earlier).

The agricultural and biogeophysical context of California is very different from that of the Midwest, as summarized below:

California Agricultural Context

- More than 350 different crops (fruit, nuts, dairy)
- Primarily relies on irrigation
- Short rainy season (November-February)

Mid-Western Agricultural Context

- A few major row crops (corn, soybeans)
- Primarily rain-fed
- Year-round precipitation

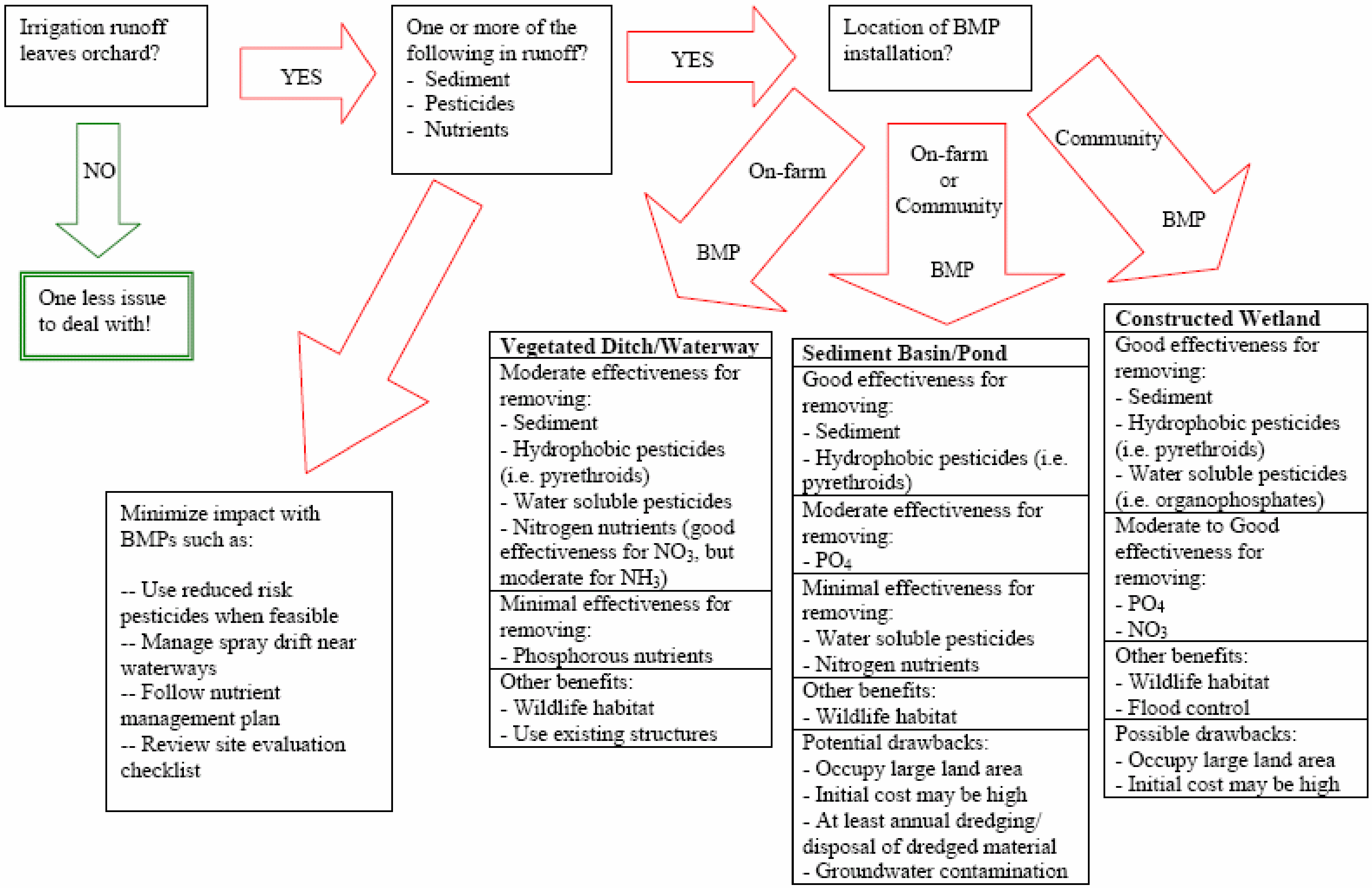
California's unique agricultural and biogeophysical characteristics impose special requirements on potential BMPs. As a result, it is important to select a single or multiple BMPs suitable specifically for implementation in California. The greatest difference between California and the Midwest is the use of irrigation which can change the effectiveness of BMPs that were developed in the predominantly rain-fed agriculture of the Midwest. In addition, California's winter rainy season coincides with pesticide applications on tree crops, which creates its own set of conditions requiring implementation of specific BMPs.

When a grower chooses a BMP, numerous factors must be considered before a final decision can be made. These factors, or a combination of factors, must be weighed so the ultimate goal – improved water quality – can be realistically attained. Generally, the decision process follows a predictable continuum where each of the steps can be examined individually. The final BMP(s) selected can range from individual field practices or a combination of practices to construction of regional water recycling and water quality control structures.

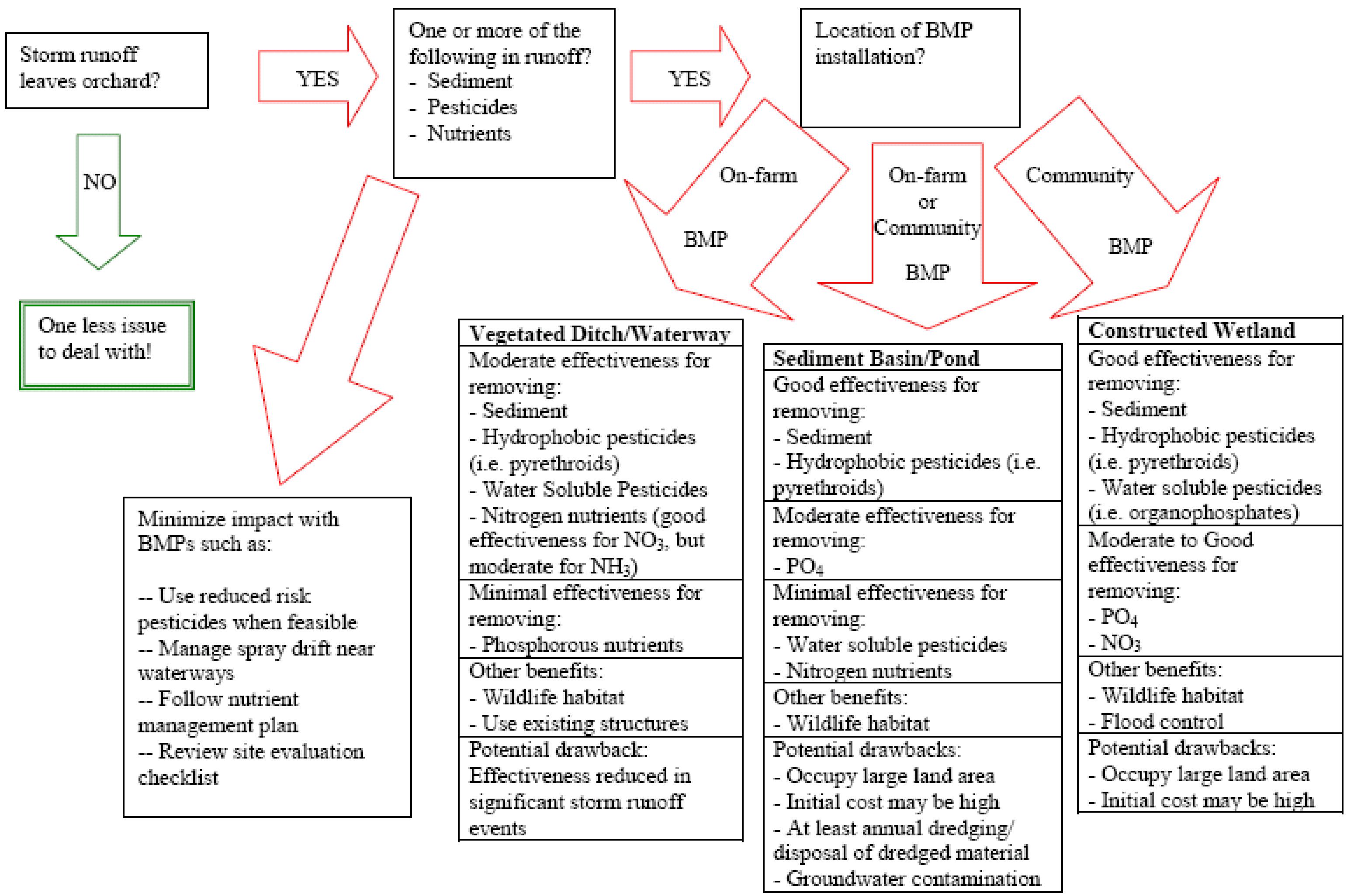
BMP Guidelines

The following charts are guidelines developed for growers in the San Joaquin Valley. The Best Management Practices selected are based on extensive research of these BMPs under local conditions. Guidelines have been developed for orchards, row crops and alfalfa for both the growing season and the dormant (storm) season.

Managing Orchard Irrigation Runoff: BMP Selection Guidelines



Managing Orchard Stormwater Runoff: BMP Selection Guidelines



Managing Row Crop Irrigation Runoff: BMP Selection Guidelines

Irrigation runoff leaves the field?

NO → One less issue to deal with!

YES → One or more of the following in runoff?
- Sediment
- Pesticides
- Nutrients

YES → Minimize impact with BMPs such as:

-- Use reduced risk pesticides when feasible
-- Manage spray drift near waterways
-- Follow nutrient management plan
-- Review site evaluation checklist

YES → Location of BMP installation?

On-farm BMPs | On-farm or Community BMP | Community BMP

Polyacrylamide (PAM) – (First irrigations after planting)	**Vegetated Ditch/Waterway**
Good effectiveness for removing: - Sediment *Limited studies on effectiveness of PAM and pyrethroid pesticides; some data show positive results.	Moderate effectiveness for removing: - Sediment - Hydrophobic pesticides (i.e. pyrethroids) - Water soluble pesticides - Nitrogen nutrients (good effectiveness for NO_3, but moderate for NH_3)
Minimal effectiveness for removing: - Water soluble pesticides - Phosphorous nutrients - Nitrogen nutrients	Minimal effectiveness for removing: - Phosphorous nutrients
Other benefits: Removes some microorganisms (potential pathogens)	Other benefits: - Wildlife habitat - Use existing structures
Potential drawback: Cationic and neutral forms can be toxic to aquatic organisms	

Sediment Basin/Pond
Good effectiveness for removing: - Sediment - Hydrophobic pesticides (i.e. pyrethroids)
Moderate effectiveness for removing: - PO_4
Minimal effectiveness for removing: - Water soluble pesticides - Nitrogen fertilizers
Other benefits: - Wildlife habitat
Potential drawbacks: - Occupy large land area - Initial cost may be high - At least annual dredging/ disposal of dredged material - Groundwater contamination
Combining Pond + PAM: - Greater effectiveness for removing sediment and hydrophobic pesticides - Note: PAM may result in slick sides of the pond, creating a possible drowning hazard for wildlife.

Constructed Wetland
Good effectiveness for removing: - Sediment - Hydrophobic pesticides (i.e. pyrethroids) - Water soluble pesticides (i.e. organophosphates)
Moderate to Good effectiveness for removing: - PO_4 - NO_3
Other benefits: - Wildlife habitat - Flood control
Potential drawbacks: - Occupy large area of land - Initial cost may be high

Managing Row Crop Stormwater Runoff: BMP Selection Guidelines

Storm water runoff leaves field?

NO → One less issue to deal with!

YES → One or more of the following in runoff?
- Sediment
- Pesticides
- Nutrients

YES → Location of BMP installation?

On-farm BMPs / On-farm or Community BMP / Community BMP

YES

Polyacrylamide (PAM) – (First irrigations after planting)	Vegetated Ditch/Waterway
Good effectiveness for removing: - Sediment *Limited studies on effectiveness of PAM and pyrethroid pesticides; some data show positive results.	Moderate effectiveness for removing: - Sediment - Hydrophobic pesticides (i.e. pyrethroids) - Water soluble pesticides
Minimal effectiveness for removing: - Water soluble pesticides - Phosphorous nutrients - Nitrogen nutrients	Minimal effectiveness for removing: - Phosphorous nutrients - Nitrogen nutrients
Other benefits: Removes some microorganisms (potential pathogens)	Other benefits: - Wildlife habitat - Use existing structures
Potential drawback: Cationic and neutral forms can be toxic to aquatic organisms	Potential drawback: Effectiveness reduced in significant storm runoff events

Sediment Basin/Pond

Good effectiveness for removing:
- Sediment
- Hydrophobic pesticides (i.e. pyrethroids)

Moderate effectiveness for removing:
- PO_4

Minimal effectiveness for removing:
- Water soluble pesticides
- Nitrogen fertilizers

Other benefits:
- Wildlife habitat

Potential drawbacks:
- Occupy large land area
- Initial cost may be high
- At least annual dredging/ disposal of dredged material
-Groundwater contamination

Combining Pond + PAM:
- Greater effectiveness for removing sediment and hydrophobic pesticides
- Note: PAM may result in slick sides of the pond, creating a possible drowning hazard for wildlife.

Constructed Wetland

Good effectiveness for removing:
- Sediment
- Hydrophobic pesticides (i.e. pyrethroids)
- Water soluble pesticides (i.e. organophosphates)

Moderate to Good effectiveness for removing:
- PO_4
- NO_3

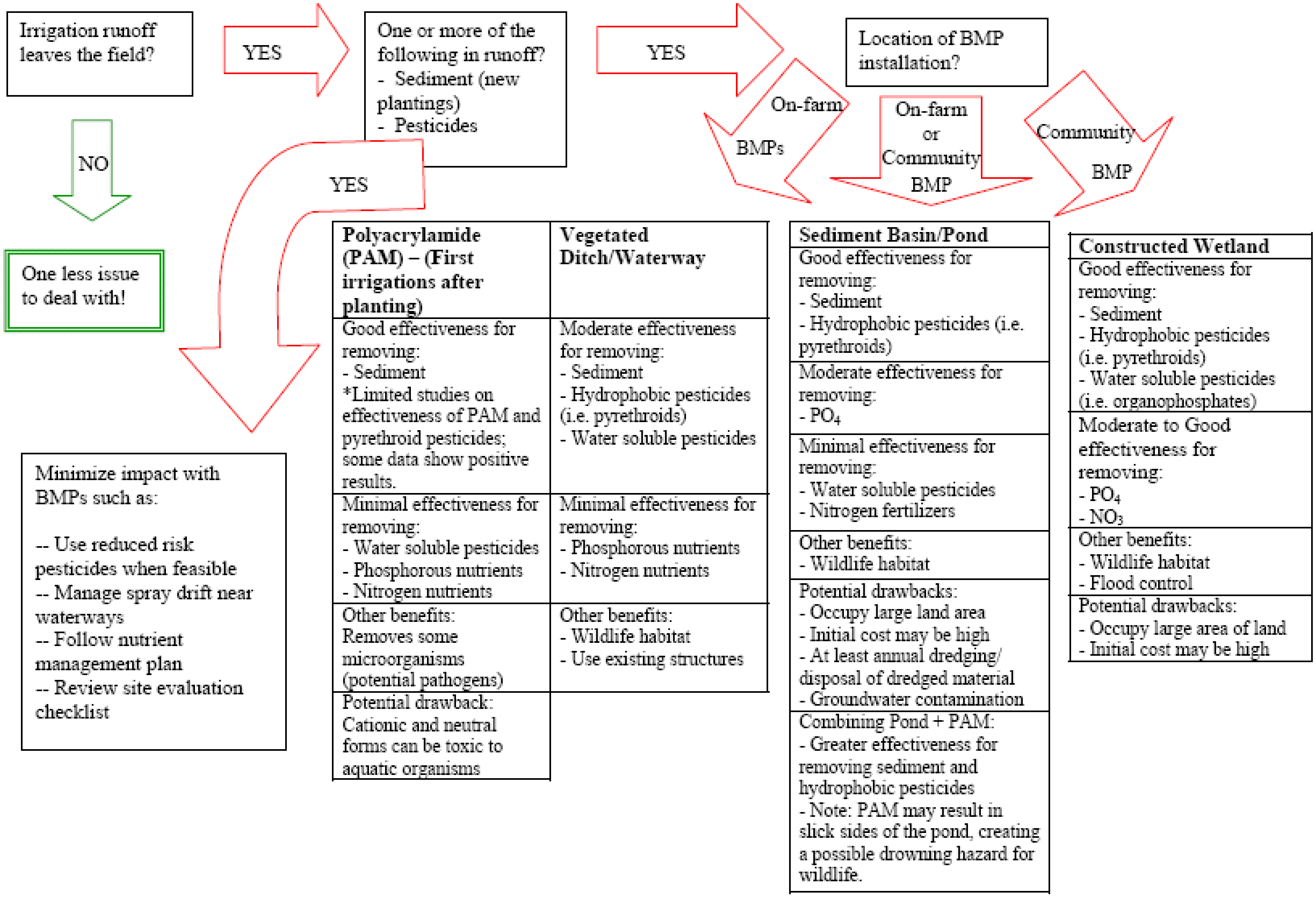
Other benefits:
- Wildlife habitat
- Flood control

Potential drawbacks:
- Occupy large area of land
- Initial cost may be high

Minimize impact with BMPs such as:

-- Use reduced risk pesticides when feasible
-- Manage spray drift near waterways
-- Follow nutrient management plan
-- Review site evaluation checklist

Managing Alfalfa Irrigation Runoff: BMP Selection Guidelines



Managing Alfalfa Stormwater Runoff: BMP Selection Guidelines

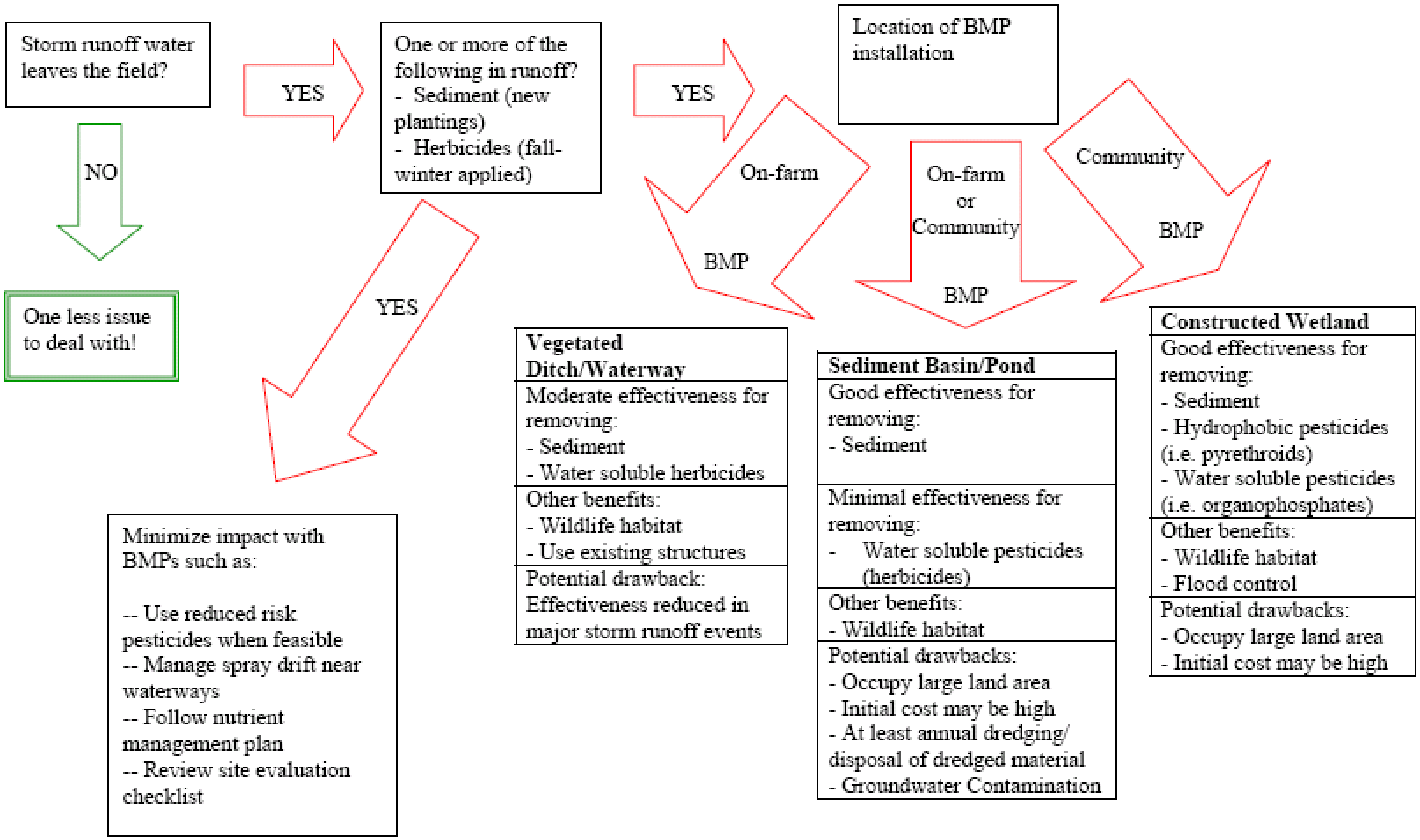


*Table1. Effectiveness of BMPs**

BMP	Sediment Removal	Pesticide Removal: Water Soluble (i.e. OPs)	Pesticide Removal: Hydrophobic (i.e. Pyrethroids)	Nutrient Removal: Phosphorous Nutrients	Nutrient Removal: Nitrogen Nutrients	Other Ecosystem Services	Potential Drawbacks
Polyacrylamide (PAM)	Good	Minimal	Unknown (predicted to be Good)	Minimal	Minimal	1. Greatly reduced sediment transport 2. Removes some microorganisms that could be pathogens	Cationic and neutral forms can be toxic to aquatic organisms
Sediment Pond	Good	Minimal	Good	Moderate for PO_4	Minimal	1. Wildlife habitat 2. Water savings 3. Catchment basins with tailwater return systems can alleviate excess runoff preventing runoff from moving into surface waters	1. Occupy a large land area 2. Initial cost may be high 3. At least annual dredging and distribution of dredged material on farm 4. Groundwater contamination
PAM + Sediment Pond	Excellent	Minimal	Good	Moderate (PO_4)	Minimal	See above	See above
Vegetated Ditch/Waterway	Moderate	Moderate	Moderate	Minimal	Moderate to Good (significantly better for NO_3 than NH_3)	1. Wildlife habitat 2. Use existing structures	Effectiveness is drastically reduced in storm runoff events
Constructed Wetland	Good	Good	Good	Moderate to Good (PO_4)	Moderate to Good (NO_3)	1. Wildlife habitat 2. Flood control 3. Provides confined area for breakdown of pesticides in water	1. Occupy large area of land 2. Initial cost may be high

* Effectiveness ratings are based on the following criteria:
<25% removal = minimal 50-80% removal = good 25-50% removal = moderate 80-100% removal = excellent

Summary of Best Management Practices

Sediment Control Basins

A sediment control basin is defined as a basin or pond formed by excavation or by constructing an embankment to temporarily store excess runoff and sediment so that sediment-laden runoff is temporarily detained under quiescent conditions, allowing sediment to settle out before the runoff is discharged.

Sediment basins used in agriculture improve water quality by trapping water, sediments, and potential pollutants. They can be effective during both the dormant and irrigation seasons. By reducing runoff rates they also minimize erosion of downstream channels and lower the possibility of flooding.

Sediment basins are located at the end of tailwater ditches and collect drainage water, allowing time for sediment in the runoff to settle out. The runoff continues to flow through the basin but flows at such a low velocity that sediment drops to the bottom of the pond. Water releases slowly through infiltration or a pipe outlet, and the quality of the water leaving the basin is improved over the quality of the water entering the basin. Basins can provide final treatment of runoff before it is released to the drainage ditch or the receiving surface water (Canessa and Hermanson 1995) or can be used in combination with a constructed wetland for additional treatment of runoff water.

If sediment basins are designed correctly, they may trap 70-80% of the sediment that flows into them (see California Stormwater BMP Handbook, 2003). Compounds that are highly hydrophobic such as the polychlorinated biphenyls (PCBs) and polyaromatic hydrocarbons, and pyrethroids bind readily to the sediment and are removed from the runoff water as the sediment settles. Although a number of papers have investigated the transport of highly hydrophobic compounds into agricultural streams with the sediment (Pereira et al., 1995; van Metre et al., 1997), to date very limited data exist on the effectiveness of sediment basins for the removal of pyrethroid residues from agricultural runoff.

In a study on pyrethroids persistence in runoff sediments, the selected pyrethroids exhibited moderate to long persistence (half-life of 2 to 17 months) in the sediments under either aerobic or anaerobic conditions. The effect of oxidation state on pesticide persistence in the sediments appeared to be pesticide specific. It was found that for most of the pesticide–sediment combinations, temperature had little effect under anaerobic conditions but was a factor in aerobic conditions. (Gan, J. et al, 2005)

Phosphorus and metals tend to be highly attracted to ionic exchange sites that are associated with clay particles and with the iron and manganese coatings that commonly occur on these small particles. Many of the persistent, bio-accumulating and toxic organic contaminants, especially chlorinated compounds including many pesticides, are strongly associated with sediment and especially with the organic carbon that is transported as part of the sediment load in rivers. Measurement of phosphorus transport in North America and Europe indicate that as much as 90% of the total phosphorus flux in rivers can be in association with suspended sediment. (Ongley, E. 1996)

Sediment basins can be very cost-effective because they can easily be created with on-farm machinery, and can be very efficient for almost all soil types, excluding highly permeable ones. To be most effective, sediment basins should be used in conjunction with other field-level erosion control practices, such as irrigation management, use of polyacrylamide, vegetated filter strips, vegetated ditches/waterways, etc. (Fiener et al. 20053). Use of these practices will also reduce the costs of maintaining the basin.

Suitable Applications

Sediment basins may be suitable for use on larger projects with sufficient space for constructing the basin. Sediment basins should be considered for implementation:

1. Where sediment-laden water may enter the drainage system or watercourse
2. At the outlet of agricultural lands between 5 acres and 75 acres
3. In association with dikes, temporary channels, and pipes used to convey runoff from disturbed areas

Advantages

1. Reduces sediment leaving property
2. Multiple constituents controlled for possible pollution reduction and enhancement of downstream water quality
3. Water recycling potential
4. Can provide near complete off-farm sediment control
5. Potential for regional approach; shared maintenance with neighbors
6. Reasonable cost for the benefit when applied on a large acreage
7. Installation in combination with other sediment management practices (PAM or vegetated ditch) can multiply the beneficial effects
8. Proven management practice

Limitations

1. Does not remove soluble pesticides
2. Requires frequent clean out; sediment mounds must be spread on fields
3. Large basins can be expensive to install and maintain and may include a loss of farmable acres
4. Low biological activity
5. Long term operational maintenance
6. Generally, sediment basins are limited to drainage areas of 5 acres or more, but not appropriate for drainage areas greater than 75 acres.
7. Sites with very fine sediments (fine silt and clay) may require longer detention times for effective sediment removal.

8. Sediment basins may become an “attractive nuisance” and care must be taken to adhere to all safety practices. If safety is a concern (for people and/or animals), basin may require protective fencing.
9. Basins with a height of 25 ft or more or an impounding capacity of 50 ac-ft or more must obtain approval from Division of Safety of Dams.
10. Standing water may provide habitat for pathogenic bacteria (such as E. coli), mosquitoes and/or other pests.

Design and Construction

Basins differ by design and capacity and may include more than one holding area on the same farm. Factors affecting design include field size, available space, access, irrigation method, soil type, and crop. The length-to-width ratio can vary, but better settling is usually achieved when its length is about three to four times greater than its width.

Implementation

General

A sediment basin is a controlled stormwater release structure formed by excavation or by construction of an embankment of compacted soil across a drainage way, or other suitable location. Basins should be located at the stormwater outlet from the site but not in any natural or undisturbed stream. A typical application would include dikes, pipes, and/or channels to divert runoff to the basin inlet as in a tailwater return system.

Planning and Location

To improve the effectiveness of the basin, it should be located to intercept runoff from the largest possible amount of agricultural area. The best locations are generally low areas. Drainage into the basin can be improved by the use of earth dikes and drainage swales. The basin must not be located in a stream but it should be located to trap sediment-laden runoff before it enters the stream.

The basin should be located in a suitable area for excavating or where a low embankment can be constructed across a swale, and where the basins can be maintained on a year-round basis to provide access for maintenance, including sediment removal and sediment stockpiling in a protected area, and to maintain the basin to provide the required capacity.

Design

Sediment basins should be designed to store at least one year’s accumulation of sediment from the contributing area. Sediment yield can be computed with assistance from the local NRCS office. If periodic removal of sediment is expected, the capacity can be reduced proportionately. Dredged sediment can be used to increase the height and therefore the capacity of the basin, or can be spread on adjacent farmland.

The USDA NRCS National Practice Standard 350 addresses the general design and installation of sediment basins. No designs specific to California farmland are available, but local NRCS technical advisors can provide site-specific specifications.

A drying area is needed so sediment can dry after it is removed. Dredged sediment can be used to increase the bank height and therefore the capacity of the basin, or can be spread on adjacent farmland. The volume of the settling zone should be sized to capture runoff from a 2-year storm or other appropriate design storms specified by the local agency. A detention time of 24 to 40 hours should allow 70 to 80 % of sediment to settle. The length of the sediment basin should be more than twice the dimension as the width; the depth should not be less than 3 ft nor greater than 5 ft for safety reasons and for maximum efficiency (2 ft of sediment storage, 2 ft of capacity). The basin(s) should be located on the site where it can be maintained on a year-round basis and should be maintained on a schedule to retain the 2 ft of capacity.

Generally, the embankment should have a minimum top width of 4 ft and side slopes of 2:1 or flatter. The embankment top and edge can be planted with annual, non-native perennial or native perennial grasses to help prevent sloughing and erosion. An outlet needs to be provided which is lower than the inlet structure/inflow level of the basin.

Grading associated with agricultural activities is not subject to General Permit requirements. If however, the grading is being done for the purpose of erecting a structure and results in a soil disturbance of one acre or greater, then the discharger should contact the local Regional Water Quality Control Board to see if the activity will need to be covered under the General Permit.

> *Note* - Agricultural activity is currently being reevaluated at Regional Board level and Regional Boards have discretion within their respective jurisdictions. It is advisable to contact your local Regional Board to ensure that the activity is not required to be permitted.

Use of PAM in Combination with Pond

In a project conducted by CURES at a field located by Orestimba Creek in western Stanislaus County near the city of Crows Landing, PAM was very effective in reducing sediment runoff based on visual observation. PAM causes soil particles to aggregate and thereby reduce soil particle movement off-site. (Western San Joaquin Valley Pesticide BMP Implementation Program, 2007)

The objective of a project in the Lower Boise River Pollution Trading Project in southwest Idaho was to measure the effectiveness of using PAM (polyacrylamide) in combination with a sediment pond. Three crop-years of data showed that applying PAM to furrows reduced sediment and total P loading to the ponds 50 to 80%, which also reduced the mass of sediment and total P retained in the ponds. In practice, the PAM-pond combination may be more effective than sediment ponds alone because PAM greatly reduces the sediment load into the ponds. Reduced sediment load increases the effective life of the pond by increasing the time between pond cleaning/dredging and decreases the gradual decline in effectiveness due to reduced retention time as the pond fills with sediment. (Bjorneberg, D.L., Lentz, R.D. 2005)

Cost

In the spring of 2005, a contractor provided an estimate for installation and maintenance for both a 30 x 200 ft and a 30 x 400 ft sediment basin in the Orestimba Creek area. Information on the depth of the basin was not provided. The costs are shown in Table 2.

Table 2. Costs for Contractor Installed Sediment Basin (2005)

Item	Costs*	
	30' x 200'	30' x 400'
Installation	$2,675	$3,175
Annual maintenance	$ 925	$1,375

*$175 equipment transport is included

U.C. Cooperative Extension also estimated the cost of a 1,600 SF water and sediment basin as a BMP for irrigated agriculture on the Central Coast (2003). The depth of the basin was 4 feet, with a total capacity of 237 cubic yards. The costs are shown in Table 3. Sizing allowances were made to assist in cost comparisons.

Table 3. U.C Cooperative Extension Costs for Sediment Basin

	Costs		
Item	**Low**	**Mid**	**High**
Installation*	$1,335	$1,921	$2,985
Annual maintenance**	$ 339	$1,333	$2,341

* To layout and mark site, clear site, excavate and compact basins, and to install pipes, couplers, and risers

** To remove and distribute sediment and to spot spray herbicide

The CALFED Water Use Efficiency Program Final Report for Yolo County Resource Conservation District (RCD) Pilot Program (2001) reported the results of their evaluation of conservation practices, including sediment traps. The RCD found that the installation costs for a small sediment trap can range from $600 to $1,000. Included in the costs were flashboard risers, which can vary in cost between $200 and $600, and excavation costs, which can vary between $200 and $500. Many of these small sediment traps were filled with sediment in only two irrigations.

Inspection and Maintenance

Maintenance costs are directly proportional to the field size and sediment yield. Reducing sediment yield before it reaches the pond will reduce the cost significantly. It is recommended that other sediment management practices be installed in conjunction with a sediment basin. The construction cost is a one time cost; maintenance is a continuous cost to keep the sediment basin operating properly.

1. Inspect sediment basins prior to forecast rain, daily during extended rain events, after rain events, weekly during the rainy season, and at two-week intervals during the non-rainy season.
2. Examine basin banks for seepage and structural soundness.
3. Check inlet and outlet structures and spillway for any damage or obstructions. Repair damage and remove obstructions as needed.
4. Check inlet and outlet area for erosion and stabilize if required.
5. Sediment that accumulates in the basin must be periodically removed in order to maintain effectiveness. Sediment should be removed when sediment accumulation reaches one

half the designated sediment storage volume. Sediment removed during maintenance may be incorporated into earthwork on the site or disposed of at appropriate locations on the farm (preferably on crop lands and areas that are not likely to erode and runoff into local waterways).

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Constructed Wetlands

Constructed wetlands are excavated shallow basins with irregular perimeters and undulating bottom contours that have a permanent pool of water throughout the year (or at least throughout the wet season). Constructed wetlands are basins into which wetland vegetation is purposely placed to enhance pollutant removal from water. The principal physical components include the aquatic vegetation, substrate for plant and microbial growth, the basin itself, associated structural devices for water management, and the water that flows through the system. Constructed wetlands and ponds have played an important role in treating wastewater from various sources.

Constructed wetlands can not only remove pollutants from agricultural runoff but also provide various ecosystem services, such as preserving or restoring the natural balance between surface waters and ground waters, and providing additional wildlife habitat and aesthetic value. As agricultural or stormwater runoff flows through the wetland, pollutant removal is achieved through settling and biological uptake within the wetland. The treatment mechanisms are a complex mix of physical, chemical, and biological processes.

Although three principal types of constructed wetlands have been used for treating wastewater, most constructed wetland systems that are proposed to minimize agricultural nonpoint source pollution in the US have been surface flow constructed wetlands. “Surface flow” constructed wetlands are systems within which the water flows over the bed surface and is filtered through the dense stand of aquatic plants. Other constructed wetland systems not considered in this discussion include subsurface flow, and floating aquatic plant systems. Much of the treatment in surface flow constructed wetland systems results from the activities of micro-organisms, principally bacteria and fungi, which thrive in this type of wetland environment. Many of the organisms become attached to submersed plant stems and litter, while others become part of the soil/plant root matrix. In addition, the entire water column is alive with micro-organisms that contribute to the treatment process.

Constructed wetlands and ponds are considered to be an important management practice for reducing runoff of nutrients, sediments and pesticides from agricultural lands. In response to historic wetland losses, the US Department of Agriculture Natural Resource Conservation Service (USDA NRCS) has established four conservation practice standards (USDA Codes 656, 657, 658, and 659) relating to constructed wetlands (USDA NRCS, 2002). By establishing these standards, farmers and other agricultural landowners are given instructions on how to develop and use constructed wetlands to minimize nonpoint source pollution of water bodies (Moore et al 2006).

Application Considerations

Constructed wetlandsare useful for wastewater treatment when a constructed wetland is a component of an agricultural wastewater management system.

Constructed wetland installation applies to sites where no natural wetland occurred historically and that contain soils that are not hydric. A constructed wetland application is appropriate in the following settings:

1. Where there is a need to achieve a reasonably high level of dissolved contaminant removal and/or sediment capture and where wetland effluent is not required to meet specific water quality discharge criteria.
2. In small to medium-sized regional tributary areas with available open space and drainage areas greater than about 10 ha (25 ac.)
3. Where base flow rates or other channel flow sources are relatively consistent year-round.
4. In settings where wildlife habitat benefits can be appreciated.

Advantages

1. Properly designed and maintained constructed wetlands with sufficient capture volume can provide significant mitigation of sediment, nutrient and pesticide contaminants in agricultural and storm water runoff.
2. If properly designed, constructed and maintained, constructed wetlands can provide substantial wildlife and wetlands habitat.
3. Regional approach to agricultural and watershed management with shared maintenance if installed cooperatively with neighboring farms.
4. Water recycling potential; effluent from the wetlands may be stored for land application.
5. Proven effective

Limitations

1. Cost of installation and maintenance and value of crop lost because of land taken out of production by the constructed wetland
2. Cooperation amongst multiple farmers/neighbors is usually required for implementation
3. Fences or other measures may be needed to exclude or minimize access of humans or animals that could be adversely affected by the constructed wetland or that would inhibit its function.
4. Mosquito and midge breeding is likely to occur in wetlands.
5. Cannot be placed on steep unstable slopes.
6. Need for base flow or supplemental water if water level is to be maintained.
7. Depending on volume and depth, pond designs may require approval from the State Division of Safety of Dams

Siting Criteria

Constructed wetlands are often utilized in smaller sub-watersheds and are particularly appropriate in areas with agricultural land uses or where high nutrient loads are considered to be potential problems. Wetlands generally consume a fairly large area (typically 4-6 percent of the contributing drainage area). Constructed wetlands may be constructed on- or off-line and can be sited at feasible locations along established drainage ways with consistent base flow. An off-line design is preferred. Locate the wetland to minimize the potential for contamination of ground water resources, and to protect aesthetic values.

Design and Sizing Guidelines

1. Facility Sizing – The basin should be sized to hold the permanent pool as well as the required runoff water volume (i.e., the volume of water treated for pollutant removal). The volume of the permanent pool should equal twice the runoff water volume. Capture volume should be sized to treat at least 85% of the annual runoff volume. Determine the

surface area using design procedures in NRCS National Engineering Handbook, Part 637, Chapter 3, Constructed Wetlands, or alternative design procedures that are recognized by the regulatory and academic conservation partners in the state.

2. Pond Configuration - The wet basin should be configured as a two stage facility with a sediment forebay and a main pool. Include energy dissipation in the inlet design to the forebay to reduce re-suspension of accumulated sediment and to facilitate maintenance. The wetland should be irregular in shape, with a length to width ratio of at least 2:1 preferably 4:1; narrowest at the inlet and widest at the outlet. Inlets and outlets must be placed far apart to avoid short circuiting (in other words, inlet water going directly into the outlet without receiving the treatment of the wetland). The length to width ratio can be increased by using high marsh areas or islands to cause incoming water to meander back and forth on its way through the system. With the proper design characteristics these wetlands can have a natural appearance and still provide all the desired functions for storm water treatment. The depth in the center of the basin should be about 4 feet deep to prevent vegetation from encroaching on the pond open water surface.
3. Pond Side Slopes - Side slopes of the basin should be 3:1 (run over rise) or flatter for grass stabilized slopes.
4. Sediment Forebay - A sediment forebay should be used to isolate gross sediments as they enter the facility and to simplify sediment removal. In this design, the runoff water volume is detained above the permanent pool and released over 24 hours. In addition to increasing the residence time, which improves pollutant removal, this design also attenuates peak runoff rates. The sediment forebay should consist of a separate cell formed by an earthen berm, gabion, or loose riprap wall. The forebay should be sized to contain 15 to 25% of the permanent pool volume and should be at least 3 feet deep. Exit velocities from the forebay should not be erosive. A maintenance ramp included in the design facilitates access to the forebay for maintenance activities and for vector surveillance and control. The bottom of the forebay may be hardened (concrete) to make sediment removal easier. A fixed vertical sediment depth marker should be installed in the forebay to measure sediment accumulation.
5. Inlet Control Structures - Provide appropriate inlet control structures to prevent debris from entering the wetland, to control the rate of inflow during normal operations, and to control inflow as necessary for operation and maintenance. When the pond is designed as an off-line facility, a splitter structure is used to isolate the runoff water volume. The splitter box, or other flow diverting approach, should be designed to convey the 25-year storm event while providing at least one foot of freeboard along pond side slopes.
6. Outlet Structure - Outlet structures and piping should be installed with collars to prevent water from seeping through the fill and causing structural failure. Outlet structures should be designed to discharge the capture volume over a period of 24 hours.
7. Emergency Spillway - Provide an auxiliary spillway or inlet bypass with sufficient capacity to pass the peak flow of the 25-year frequency, 24-hour duration storm and provide erosion protection for the perimeter embankment.
8. Soil/Topography - Soil at the site proposed for a created wetland must be suitable to allow for sufficient water retention, infiltration and wetland plant growth. For wetland vegetation, soils must be suitable, from the ground surface to below the static water level. In areas with porous soils an impermeable liner may be required to maintain an adequate permanent pool level. It may be necessary to stockpile topsoil during construction and

later overlay it along the wetland bottom and side slopes. The topography of the site proposed for a created wetland must also be considered. Steep side slopes surrounding the wetland should be avoided since they will deter the growth of wetland vegetation, which in turn increases problems with sediment removal and maintenance. Minimal excavation is preferred to reduce constructions costs and to produce a more natural looking wetland. Knowing the location of the water table is an important aid in designing areas that will have standing water. Measures for controlling seepage may be designed according to the procedures in NRCS National Engineering Handbook, Part 651, Agricultural Waste Management Field Handbook, Appendix 10d, "Geotechnical Design and Construction Guidelines."

9. Vegetation - A plan should be prepared that indicates how aquatic and terrestrial areas will be vegetatively stabilized. Wetland vegetation elements should be placed along the aquatic bench or in the shallow portions of the permanent pool. The optimal elevation for planting of wetland vegetation is within 6 inches vertically of the normal pool elevation. Wetland vegetation should occupy no more than 50% of surface area and be comprised generally of diverse, local aquatic plant species. When selecting vegetative species, give priority to native wetland plants collected or grown from material within the Major Land Resource Area (MLRA) of the Constructed Wetland location, and consider the potential to transport chemical contamination from the wetland plant site to the constructed wetland.
10. Access Road - To facilitate vector surveillance and control activities, road access should be provided along at least one side of wetlands that are seven meters (23 ft) or less in width. Those wetlands that have shoreline-to-shoreline distances in excess of seven meters should have perimeter road access on both sides or be designed such that no parcel of water is greater than seven meters from the road.

Construction/Design Considerations

Prepare plans and specifications for each specific field site where a constructed wetland will be installed. Define the purpose, goals, and objectives of the practice and the soils, hydrology and vegetation criteria. Include information about the location, construction sequence, and vegetation establishment. Incorporation of a sediment forebay as a pretreatment design feature helps to settle out coarse sediment particles from the water inflow. By removing these particles from runoff before they reach the large permanent pool, the maintenance burden of the pond is reduced. Coarse particles remain trapped in the forebay, and maintenance is performed on this smaller pool, eliminating the need to dredge the entire pond. A sediment forebay can also slow the velocity of the water into the permanent pond during high stormwater events. Effective wetland design displays "complex microtopography." In other words, wetlands should have zones of both very shallow (<6 inches) and moderately shallow (<18 inches) wetlands incorporated, using underwater earth berms to create the zones. This design will provide a longer flow path through the wetland to encourage settling, and it provides two depth zones to encourage plant diversity. There are a variety of sizing criteria for determining the volume of the permanent pool, mostly related to the runoff water volume (i.e., the volume of water treated for pollutant removal) or the average storm size in a particular area. Generally, a simplified method (i.e., permanent pool volume equal to twice the runoff water volume) is recommended.

Maintenance

The amount of maintenance required for a constructed wetland is highly dependent on local regulatory agencies, particular health and vector control agencies. These agencies are often extremely concerned about the potential for mosquito breeding that may occur in the permanent pool. Ponds should be designed with a maintenance access to the forebay to ease this relatively routine (every 5–7 year) maintenance activity. In addition, ponds should generally have a drain to draw down the pond for vegetation harvesting or the more infrequent dredging of the main cell of the pond. Vegetation harvesting in the summer is recommended. Typical maintenance activities and frequencies include:

1. Schedule semiannual inspections for burrows, sediment accumulation, structural integrity of the outlet, and litter accumulation.
2. Remove accumulated trash and debris in the basin at the middle and end of the wet season.
3. Where permitted by the Department of Fish and Game or other agency regulations, stock constructed wetlands regularly with mosquito fish (*Gambusia spp*.) to enhance natural mosquito and midge control.
4. Consider bat boxes and other measures to control vectors and nuisance insects. Maintain vegetation to assist the movements of mosquito fish to control mosquitoes, as well as to provide access for vector inspectors. An annual vegetation harvest in summer appears to be optimum, in that it is after the bird breeding season, mosquito fish can provide the needed control until vegetation reaches late summer density, and there is time for re-growth for runoff treatment purposes before the rainy season. In certain cases, more frequent plant harvesting may be required by local vector control agencies.
5. Maintain emergent and perimeter shoreline vegetation as well as site and road access to facilitate vector surveillance and control activities.
6. Remove accumulated sediment in the forebay and regrade about every 5-7 years or when the accumulated sediment volume exceeds 10 percent of the basin volume. Sediment removal may not be required in the main pool area for as long as 20 years.

Construction Cost

Construction cost data for wetlands are rare, but one simplifying assumption is that constructed wetlands are typically about 25 percent more expensive than storm water ponds of an equivalent volume. Using this assumption, and the information presented above on sediment ponds, a 1600 square foot wetland would cost approximately $3,700. (Brown, W., Schueler, T., 1997)

In an interview with, Vince Thompson of Ducks Unlimited, he provided some general cost estimates for wetland installation as a range of $400-1000/acre, with the average project costing about $750 per acre for planting, survey, design and construction. The cost may be as low as $400 per acre in some cases if there is existing topography that may be utilized, but in general, restoration work where agricultural fields are converted to wetlands, construction costs range from $500-900 per acre. In some cases where riparian planting, survey, site design and construction management are involved, costs can range from $600-1000 per acre. (Markle, J. 2007?)

Maintenance Cost

For ponds, the annual cost of routine maintenance has typically been estimated at about 3 to 5 percent of the construction cost; however, the published literature is almost totally devoid of actual maintenance costs.

Effectiveness of Constructed Wetlands

Constructed wetlands can be very effective for removing pollutants such as sediment, nutrients, and pesticides from agricultural waste water. The primary benefit of vegetation in wetlands is its ability to reduce organic and suspended solids. Another benefit is that the plant and associated litter layer provides natural habitat for beneficial microbial organisms. Vegetation processes water by storing nutrients in biomass, encouraging sedimentation, and providing habitat for beneficial microbial communities (Luckeydoo et al. 2002). Recent studies have shown the importance of aquatic vegetation for mitigation of pesticide influx through wetlands and agricultural drainage ditches (Bennett et al., 2005, Moore et al., 2001a, Schulz et al., 2003c and Schulz et al., 2003b).

A summary of the effectiveness of constructed wetlands to treat runoff for various pollutants is presented in Table 4 (the references upon which the range is based are given in the right column).

Table 4. Range of Effectiveness of Constructed Wetlands for Reducing Contaminants

Pollutant	Effectiveness Range	References
Sediment	73 - 100%	Higgins et al., 1993
Pesticides	42 - 90%	Moore et al., 2000 , 2002 ; Schulz et al., 2003a , 2003b , 2003c , Schulz 2004 ; Milam et al., 2004
Nitrogen	>50%	Brix, 1994
Phosphorous	1 - 100%	Braskerud et al., 2005; Higgins et al., 1993

Pesticides and Sediments

Studies on using constructed wetlands to treat polluted water begin as early as the 1970's. Moore et al (2004, 2001 and 2002) investigated the use of constructed wetlands to mitigate the agricultural runoff of pesticides atrazine, lambda-cyhalothrin, metolachlor and chlorpyrifos. In the case of chlorpyrifos, they found that chlorpyrifos rapidly sorbed to sediment and plant material, with approximately 47-65% of measured chlorpyrifos mass retained within the first 30-36 m of wetland mesocosms. Of the measured mass approximately 55% and 25% was retained by sediments and plants, respectively.

Nutrients

<u>Nitrogen</u>

The dominant forms of nitrogen in wetlands that are of importance to wastewater treatment include organic nitrogen, ammonia, ammonium, nitrate, nitrite, and nitrogen gases. Inorganic forms are essential to plant growth in aquatic systems but if scarce can limit or control plant productivity. The nitrogen entering wetland systems can be measured as organic nitrogen, ammonia, nitrate and nitrite. Total Nitrogen refers to all nitrogen species. The removal of nitrogen from wastewater is important because of ammonia's toxicity to fish if discharged into water courses. Excessive levels of nitrates in drinking water are thought to cause methemoglobinemia in infants, which decreases the oxygen transport ability of the blood. In a review of 19 surface flow wetlands (US EPA, 1988) it was found that nearly all reduced total nitrogen. In a review of both surface flow and subsurface flow wetlands, Reed (1995) concluded that effluent nitrate concentration is dependent on maintaining anoxic conditions within the wetland so that denitrification can occur. He found that subsurface flow wetlands were superior to surface flow wetlands for nitrate removal. The 20 surface flow wetlands reviewed reported effluent nitrate levels below 5 mg/L; the 12 subsurface flow wetlands reviewed reported effluent nitrate ranging from <1 to < 10 mg/L. Results obtained from the Niagara-On-The-Lake vertical flow systems show a significant reduction in both total nitrogen and ammonia (> 97%) when primary treated effluent was applied at a rate of 60L/m^2/day. Calculations made showed that over 50% of the total nitrogen going into the system was converted to relatively harmless nitrogen gas. (Lemon et al., 1997).

<u>Phosphorus</u>

In freshwater aquatic ecosystems phosphorus has been described as the major limiting nutrient. Under undisturbed natural conditions, phosphorus is in short supply. The natural scarcity of phosphorus is demonstrated by the explosive growth of algae in water receiving heavy discharges of phosphorus-rich wastes. Because phosphorus, unlike nitrogen, does not have an atmospheric component, the phosphorus cycle can be characterized as closed. The removal and storage of phosphorus from wastewater can only occur within the constructed wetland itself. According to Mitsch and Gosselink (1986) phosphorus may be sequestered within a wetland system by the binding of phosphorus in organic matter as a result of incorporation into living biomass, and by precipitation of insoluble phosphates with ferric iron, calcium, and aluminum found in wetland soils.

Higher plants in wetland systems may be viewed as transient nutrient storage compartments absorbing nutrients during the growing season and releasing large amounts of nutrients at senescence (Bernard and Solsky, 1976; Guntensbergen, 1989). According to Sloey et al. (1978) vascular plants may account for only a small amount of phosphorus uptake with only 5 to 20% of the nutrients detained in a natural wetland being stored in harvestable plant material

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Vegetated Ditches/Grassed Waterways

Vegetated waterways include grassed waterways and vegetated ditches. A vegetated waterway is a natural or constructed channel with permanent vegetation that is shaped and graded to carry surface water at a nonerosive velocity to a stable outlet (NRCS, 1997). Vegetation in the ditch protects the soil from erosion and traps sediment, pesticides, nutrients, and potentially pathogenic microorganisms being transported in agricultural runoff. Vegetated ditches are mainly manmade agricultural ditches. Studies of vegetated ditches promote the use of historical drainage ditches already present in the agricultural production landscape. A majority of grassed waterways, on the other hand, are natural channels. The pollution reduction mechanisms are the same for both vegetated ditches and grassed waterways, and the factors affecting their effectiveness are similar.

Suitable Applications

Vegetated ditches/grassed waterways may be suitable at sites where concentrated runoff needs to be conveyed and controlled without causing erosion. Vegetated waterways should be considered for implementation on relatively flat sites at drainage outlets.

Advantages

1. Helps slow the flow of water to a non-erosive level.
2. Provides a means of trapping sediment, nutrients, and pesticides while preventing gully erosion.
3. Provides habitat and cover for wildlife.

Limitations

1. Storm flows can be restricted by overgrown channels causing waterway breaching and flooding.
2. Due to the concentrated flow that normally occurs in waterways, sediment trapping and water infiltration can be minimal with large runoff events, but substantial with smaller events.

Design and Implementation

Cross-section shape and length of side slopes

The shape of the cross section and the length of the side-slopes of the vegetated waterways are two of the most important parameters determining the effectiveness of runoff reduction.

1. In California it is preferable to construct the vegetated ditch with a V-shaped cross section as opposed to a “U-shaped” cross section (Moore et al., 2008).
   Note: in the Midwest, the u-shaped vegetated ditch is more effective than the V-shaped vegetated ditch (Fiener and Auerwald, 2003a).
2. As a general rule, the total surface area of the vegetated ditch should be approximately 1% of the total drainage area (IDEQ 2005).
3. A wider design maximizes flow residence time and promotes pollutant removal by settling, filtration, and some absorption and uptake of dissolved pollutants through the use of properly selected vegetation.

4. A maximum bottom width should be designed to accommodate uniform sheet flow with average depth between 1 and 3 inches for maximum effectiveness.
5. A minimum 2-foot bottom width is recommended to facilitate swale mowing with standard lawn mowers. However, narrower widths are possible if space is very constrained.
6. The vegetated ditch should have side slopes no steeper than 3:1 run over rise and provide at least 1 foot of freeboard (IDEQ 2005).
7. Longer side slopes increase the travel time of runoff flow into the bottom of the channel, which increases infiltration.

Length and slope of ditch
'Length' here has the meaning of 'length along the channel' and is in contrast to the length of the side slope, which is more akin to the width of an on-site buffer).
1. The slope along the length of the ditch should not exceed 6%. Generally between 2% and 4%; slopes greater than 4% may require check dams.
2. The optimum length of the vegetated ditch depends on the targeted pollutants and should be considered together with other design factors, i.e. ditch shape and side slope.
3. The longer the runoff remains in the ditch, the more chemicals and sediment can be removed - undersized buffers have little to no positive impact on water quality.
4. Residence time of the runoff should be at least 5 minutes (10 minutes is preferable).
5. Removal of finer particles and nutrients (i.e. phosphate) require longer vegetated ditches.
6. Depending on site specific factors, 100m to 280m of vegetated ditch are necessary for effective mitigation of atrazine from runoff (Moore et al., 2002).
7. 510m of vegetated ditch are required to decrease aqueous esfenvalerate to 0.1% of the initial exposure (Cooper et al., 2002).

Installation and management of vegetation
1. Vegetation that is well suited to survive in the site conditions and that may provide wildlife habitat should be considered.
2. Long-lived, deep rooted, stiff stemmed, low growing (no taller than 6 inches) perennial grasses that increase soil porosity and decrease soil bulk density should be selected to provide good infiltration characteristics (Boyd et al. 1999). The extensive root growth in healthy perennial vegetation also increases biological activity by supplying an organic carbon energy source to soil microorganisms. These microorganisms are responsible for degrading pesticides and denitrifying nitrate. For example, microbial degradation is the primary means of diuron dissipation from soil (Moncada, undated), and microbes also degrade the organophosphate pesticides chlorpyrifos and diazinon (CIWMB, 2002). Pesticides and nutrients may also be taken up by roots and metabolized in plants. In addition, the vegetation itself adsorbs pesticides during runoff events.
3. Native hydrophytic plants that can tolerate periods of drought, such as certain sedge and rush species, are also well suited for vegetated ditches (Solano RCD and Yolo RCD 2006).
4. If considerable water flow is expected prior to establishment of permanent, vigorous vegetation, erosion control blanket, netting or mesh should be properly installed to stabilize the sediment in the ditch until the vegetation is well established.

5. To be effective, the depth of the runoff during treatment should not exceed the height of the grass.
6. It is recommended that the vegetation in the ditch be cut/mowed once per year. However timing the cut should be planned based on your runoff patterns as the vegetation will better filter contaminants from runoff when it is in a rough/uncut state (Fiener and Auerswald, 2003a).
7. If excess sediment accumulates in the ditch, it will need to be removed and the vegetation repaired/reseeded.
8. Reseed areas of the ditch that have been damaged by equipment, herbicides, or erosion.

Cost

Vegetated waterways are relatively inexpensive management practices. The cost for installing and maintaining a vegetated ditch/grassed waterway may include:

1. Loss of harvestable land unless an existing ditch will be used.
2. Cutting in and grading the ditch.
3. Seeding/planting the ditch.
4. Erosion control measures prior to establishment of permanent vegetation.
5. Mowing (annually) and removal of sediment (as needed following large storm events or long periods of continual use).

Summary of the Effectiveness of Vegetated Ditches/Grassed Waterways for Mitigating Various Contaminants in Runoff

When properly installed and maintained, vegetated waterways are effective for reducing sediment, pesticides, and phosphorous nutrients in agricultural runoff. The following tables give a summary of the effectiveness of vegetated waterways to keep various pollutants from traveling into larger water bodies. The references upon which the range is based are provided in the tables.

Table 5. Range of Effectiveness for Various Pollutants

Pollutant	**Effectiveness Range**	**References**
Runoff Volume	10-91.2%	Chaubey et al, 1994; Vianello et al, 2005
Sediment	30-100%	Gassman et al, 2006; Patty et al, 1997; Abu-Zreig, 2004
Pesticides	27-100%	Hall et al, 1983; Mersie et al, 1999; Rankins et al, 2001; Watanabe and Grismer, 2001
Total Nitrogen	27-96%	Dillaha et al, 1988, 1989; Uusi-Kamppa et al, 2000; Gassman et al 2006
Nitrate	7-100%*	Patty et al, 1997; Barfield et al, 1998
Phosphorous	22-91%*	Dillaha, 1989; Patty et al, 1997; Gassman et al, 2006; Chaubey et al, 1995

* An early study found that the grassed waterway was not efficient in reducing nitrates but could reduce phosphorus by 90-95% (Meuleman and Beltman, 1993).

Table 6. Results of Specific Studies - Sediment Reduction:

Study	**Effectiveness**	**Comments**
Fiener and Auerswald, 2003a	77%, 97%	managed (cut vegetation) vs. unmanaged – better performance by unmanaged vegetation
Fiener and Auerswald, 2003b	82%	

Table 7. Results of Specific Studies - Pesticide Reduction:

Study	Effectiveness	Comments
Asmussen et al, 1977	70%	80 ft long waterway; 2,4-D (water soluble herbicide)
Bennett et al, 2005, Cooper et al, 2004	as high as 99%	reduction in esfenvalerate, lambda cyhalothrin, bifenthrin
Briggs et al 1999	56%	simulations and onsite nursery research; isoxaben + oryzalin, isoxaben + trifluralin
Cahn et al, 2008	56%	Reduction in pyrethroid discharge with 50m veg. ditch
Gill, 2008	38%	median reduction in chlorpyrifos with 200m veg. ditch
Moore et al, 2008	50%	Reduction in trans-permethrin and cis-permethrin with 21-22m of veg. ditch; reduction in diazinon with 55m of veg. ditch
Milam et al, 2004	90%	methyl parathion
Moore et al, 2002	47-65%	chlorpyrifos; 47-65% retained within first 30-36 m
Moore et al, 2001	63% and 83%	Removal of atrazine and lambda-cyhalothrin respectively with 50 m veg. ditch

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Polyacrylamide (PAM)

Polyacrylamide (PAM) has been used to improve agricultural runoff water quality by reducing sediments, nitrogen, dissolved reactive phosphorus and total phosphorous, pesticides, weed seeds and microorganisms. PAM's high effectiveness and low cost, coupled with its ease of implementation, have resulted in a rapid adoption of this technique by growers. About 800,000 hectares of US irrigated land use PAM for erosion and/or infiltration management (Sojka et al., 2006).

The term polyacrylamide (PAM) is a generic chemistry term that refers to a broad class of long- chained, high molecular weight polymeric compounds. There are hundreds of specific PAM formulations, varying in polymer chain length and number and kinds of functional group substitutions, and they have many industrial uses. PAM formulations are used to accelerate separation of solids from aqueous suspension in agricultural runoff, paper manufacture, sewage sludge dewatering, food packaging, mining, and clarification of refined sugar (Sojka, 2001).

PAM formulations for irrigated agriculture are water soluble, large anionic polymers with typical molecular weights of 12–15 million grams per mole (more than 150,000 monomer units per chain) (Orts et al., 2002). Soil particles are attracted to PAM through an ionic attraction of opposite charges between polymer and soil particles, creating large stable aggregates of PAM and soil. Soil aggregates are further stabilized by chain bridging whereby a single polymer chain spans between separate soil particles. The high molecular weight of the polymer allows chains to interact with multiple particles, creating a network of stabilized particles that effectively resist the erosive force of water.

Although polymers were adapted and used in agriculture in the early 1950s, and they did improve plant growth by stabilizing soil aggregates, hundreds of pounds per acre needed to be used. PAM was sprayed and tilled onto fields using as much as 100-300 kilogram/hectare in order to modify soil structure in the entire tilled surface layer, resulting in material and application costs that were prohibitively high (Weeks and Colter, 1952).

By the 1980s polymer costs, formulations, and purity had improved. Mitchell (1986) first noted that sediment in runoff was reduced when irrigating furrows after pretreatment with PAM. Further work showed that low rates could be used to control furrow erosion (Lentz et al., 1992 and Malik et al., 1991) and that only a thin veneer over a soil surface protected against erosive forces.

During the 1990s water soluble polyacrylamide was fully recognized as a highly effective erosion-preventing and infiltration-enhancing polymer when applies at rates of 1-10 ppm in furrow irrigation water (as summarized in Sojka, 2001). In field studies, PAM reduced an average of 94% (80-99% range) sediment loss in field runoff from furrow irrigation, and typically increased by 15-50% relative infiltration on medium to fine textured soils compared to untreated controls (Sojka et al., 2000; Sojka and Lentz, 1997; Sojka et al., 1998). Lenz and Sojka (1994) found that sediment loss on freshly cultivated furrows applied with PAM was 6% of untreated furrows (application rate of 1.3 kilogram/ hectare). There is a dramatic visual effect when PAM is used (Figures 1 and 2). Water that runs off of furrows not treated with PAM is always turbid and sediment-laden and furrow bottoms within the field show erosional scouring and sediment transport and redeposition. When PAM is used at proper rates, water in both the furrow and leaving the field is perfectly clear, and there is no evidence of erosion and redeposition within furrows.

PAM formulations have been commercially sold in the United States since 1995 for reducing irrigation-induced erosion and enhancing infiltration. Its use in the U.S. has steadily increased since then, and is expected to continue to increase as new water quality requirements are mandated by federal, state, and local regulations, and because PAM is one of the most effective and economical technologies recently identified that accomplishes the needed water quality improvements. Its use is also increasing in Canada, and in diverse places such as Australia, Central America, Africa, Spain, Portugal, France, and Israel (Sojka 2001). Although its use in California has generally lagged behind that in other western states, current research on the Central Coast shows it to be highly effective (Cahn et al. 2004). PAM's many forms and application techniques make integration into the farmers' irrigation routine smooth and relatively easy once the initial set-up is complete.

Suitable Applications

PAM may be suitable for application on farms with small to medium acreage. PAM should be considered for implementation:

1. on farms with small to medium acreage
2. where sediment transport in irrigation runoff is a problem
3. where the appropriate staff to dispense the PAM during irrigation are present
4. when other BMPs (i.e. sediment basin) can be implemented in combination with PAM for maximum reduction of sediment, pesticides, and nutrients

Advantages

1. Reduction of sediment in runoff (avg. 94%)
2. Reduction of nutrients (nitrogen and phosphorous) in runoff (avg. 85-98%)
3. Reduction of microorganisms (potential pathogens) in runoff (avg. 30-50%)
4. Reduction of hydrophobic pesticides (chlorothalonil, endosulfan) in runoff (49%-54%)
5. Increased infiltration in medium to fine soils → reduced volume of runoff (conservation of irrigation water) (avg. 15-50% depending on soil type)

Limitations

1. Little to no increase (or even a decrease) in infiltration in course soils.
2. Little to no reduction of water soluble pesticides in runoff.

Design and Implementation

NRCS Conservation Practice Standard (NRCS 2001)

1. PAM must be of the anionic type meeting acrylamide monomer limits of ≤0.05%, have a charge density of 10 to 55%, and have a molecular weight of 6 to 15 mg/mole.
    a. Cationic or nonionic polymers should not be used (they can result in toxicity to aquatic organisms.). Anionic PAM should be selected.

Slope of field

1. At steep slopes, higher PAM application rates are required to enhance the final infiltration rate in order to reduce the runoff and soil erosion.
    a. A PAM application rate of 4 kg per hectare is the most appropriate for soil erosion reduction at slopes of 5.0% and 7.5% (Sepaskhah and Bazrafshan-Jahromi, 2006).
2. In fields with little slope, PAM is effective at low rates of application (as low as 1 kg per hectare per season) (Sojka, 2001).

Soil type/grain size

The type of soil is important when considering PAM as an agricultural management practice.

1. PAM is most effective for reducing sediment in runoff in medium to fine textured soils.
2. In coarse textured soils, there have been reports of no infiltration effect or even slight infiltration decreases with PAM (Sojka et al., 1998).
    a. If the soil is very sandy, a slight decrease in infiltration may be beneficial.

Effects of PAM on Infiltration

The advance of irrigation streams in fine or medium textured soils is often slowed when PAM is in the water, especially for the initial irrigation on new furrows. This is because the infiltration rate is usually higher. PAM may result in an increase in infiltration of up to 50% in heavy soils, with 15% being typical on medium textured soils (NRCS, 2001; Sojka et al., 1998a; Sojka and Lentz, 1997). PAM accomplishes this because it preserves soil structure during rapid wet up and inhibits the formation of surface seals by dispersed soil particles. PAM also increases soil pore continuity by stabilizing soil aggregates, especially in fine textured soils (Sojka et al., 2000).

Because PAM prevents erosion in furrow bottoms and sealing of the wetted perimeter, lateral water movement increases about 25% in silt loam soils. This, coupled with increased porosity, can allow significant water conservation, especially during early irrigations. Farmers can improve field infiltration uniformity by increasing inflow rates (up to 2-3 times faster than normal inflow rates) at the beginning of the irrigation. This reduces infiltration time differences between inflow and outflow ends of furrows (Sojka el al., 1998b). This practice, known as surge irrigation, is possible because PAM prevents upper field scouring from the increased water flow. Once water reaches the end of the furrow and runoff begins, inflows must be reduced to a rate that just sustains the furrow stream at the outflow end of the field.

In coarse textured soils there is little increase in pore continuity resulting from PAM. In these sandy soils, infiltration is usually not increased and may be reduced (Malik and Letey, 1992). Because of this, PAM can be used to decrease infiltration rates in sandy soils lacking dispersible clays and silts (Lentz, 2003). This can be a valuable water conservation tool on coarse-textured soils where infiltration is fast. It can also reduce leaching of nutrients and pesticides. Generally, higher application rates are necessary to achieve this effect. Rates at 50 kg/ha (48 pounds per acre) achieved this effect experimentally. Experimental work is also currently being conducted to ascertain if PAM can be used to limit seepage loss from canals and irrigation ponds (Lentz, 2003).

Reduction in Nutrient and Mineral Loss Resulting from PAM

Because PAM reduces the concentration of sediment carried off of a field, it also reduces the concentration and amount of nutrients leaving the field because many nutrients are bound to or contained in sediment particles. It is very effective in reducing nutrient movement from irrigated fields. In one recent study, Entry and Sojka (2003) found that water flowing in furrows receiving PAM treatments had reduced nitrate concentration in runoff by 85% and reduced total phosphorus by 90%. Other researchers have also found that PAM greatly reduces total phosphorus and dissolved reactive phosphorus losses (Lentz et al., 1996; Lentz et al., 1998) and nitrate and total nitrogen (Bahr and Steiber, 1996). Its effect on nitrate-nitrogen was less pronounced than for total nitrogen due the fact that nitrate nitrogen is water soluble. Movement of other nutrients such as calcium, magnesium manganese, iron copper, boron, and zinc were also reduced (Entry and Sojka, 2003). In California, PAM reduced the load of total phosphorus and nitrogen in tailwater in vegetable fields (Cahn et al., 2004).

Influence of PAM on Other Water Pollutants

In addition to greatly reducing soil erosion, PAM protects surface waters from sediment and other contaminants washed from eroding fields. Studies have shown that this includes pesticides (Oliver and Rai, 2006; Singh et al., 1996; Bahr and Steiber, 1996) biologically oxygen demanding substances, and potentially pathogenic microorganisms (Wood, 2002; Sojka and Entry, 2000).

Use of PAM in Furrow Irrigation

The Natural Resources Conservation Service (NRCS) recommends that the concentration of PAM in irrigation water be about 10 ppm (2001). This translates to a standard application rate of 1-2 kilograms per hectare, or a little less than 1-2 pounds per acre (1 kilogram/ hectare = 0.9 pounds per acre).

The type of application method used, and the rate of application, is based on field conditions and system requirements. PAM is generally most effectively used during the first irrigation or pre-irrigation and after any soil disturbance such as recontouring beds or furrows. Additional use is necessary only if erosion is seen, as evidenced by sediment in the water at the tail end of furrows. If the water leaving the end of the furrow is clear, no erosion is occurring. If subsequent applications are found to be necessary, they are usually at a rate much lower than the initial application. Farmers typically use 3-5 kilogram/hectare (2.7-4.5 pounds/acre) over the course of a season, depending on site conditions and on the number of cultivations and irrigations (Sojka, 2001).

In one popular application method called dry or "patch" treatments, granular PAM is applied at the head of each furrow as an initial dose before irrigation begins. The PAM dissolves during the furrow advance period. Typical patch doses are 15 to 30 grams (0.5–1.0 ounce) per furrow. The amount of PAM can be determined on an area-equivalent basis (furrow spacing multiplied by length) at a 1-2 kilogram/hectare (0.9–1.8 pounds/acre) field application rate. The PAM is placed over the first 1–1.5 meters (about three to five feet) of the furrow. Turbulence from the water entering the furrow helps dissolve the PAM, creating a sort of thin gel-slab of PAM at the top of the furrow that additional water slowly dissolves and carries down the furrow (Nishihara and Shock, 2001). The PAM needs to stabilize only the first few millimeters of soil in each furrow to be effective.

Residual erosion control often occurs during subsequent irrigations because small areas of the patch are often still intact at the end of the first irrigation. Lentz and Sojka (2000) found that this method of initial dose application during the furrow advance period controlled erosion better than either applying multiple smaller, divided doses initially and throughout the irrigation cycle, or applying PAM continuously.

The patch method works well in most situations, but is less reliable on very steep slopes (greater than about 3%) or where inflow rates are very high (about 12 gpm). These conditions can cause the PAM to break up and move down the furrow or the patch to be buried by soil scoured at the inflow point. In these cases, liquid PAM or PAM-calcium formulations can be metered directly from a container into an irrigation ditch, directly into the furrow, or through a pipe line or injector pump. PAM-calcium formulations have the added benefit of supplying calcium to the soil, which can help ameliorate structural problems in soils with high sodium content. Dry formulations of PAM can also be pre-dissolved in the advancing inflow, in the head ditch or the delivery pipe. To properly dissolve, turbulence must be created, for instance, by metering PAM granules just below drop structures. In this case, care must be taken to keep the metering system completely dry. PAM blocks or cubes can also be placed in wire baskets secured to the edge of a ditch. Liquid application is also recommended instead of the patch method when surface soil is damp.

Use of PAM with Sprinkler Irrigation

Polyacrylamide can also be used in sprinkler irrigation. As with furrow irrigation, it effectively reduces runoff and soil loss. It especially improves infiltration where the water drops hit the soil surface. In addition to reducing runoff problems, it also improves irrigation uniformity and reduces problems with stand establishment when water ponds in low areas of the field. The precision of water and chemical applications also improves because infiltration occurs where water drops hit the soil. Aggregate stability is also increased (Smith et al., 1990).

The amount of PAM required is higher than for furrow irrigation for the same level of control, because the PAM has to protect a larger area of soil. In controlled field studies, Aase et al. (1998) found that application rates of 2-4 kilogram/hectare (0.9-1.8 pounds/acre) reduced runoff 70% and soil loss 75%. Both Bjorneberg and Aase (2000) and Bjorneberg et al. (2000) found that it took about three times the amount recommended for furrow irrigation to control the same acreage, and that multiple applications reduced runoff better than single applications. A single application of 2–4 kg/ha (1.8–3.6 pounds per acre) could be used for critical irrigations such as seedling emergence or before crop cover is established, but multiple PAM application and crop residue should be used for season-long runoff and soil erosion control. Three applications of 0.9 pounds per acre (1.0 kg/ha) controlled runoff longer than a single application of 2.7 pounds/acre (3 kg/ha). However, in Central Coast soils an application rate of 5 kg/ha (4.5 pounds per acre) was found effective in improving the quality of tailwater runoff (Cahn et al., 2004).

Cost

Annual application rates including labor range from about $10-$30 per acre* (CWI, 2006)

*There is a net savings (rather than expense) when the cost of nutrient fertilizers retained on site is included in the calculation.

Dry/granular PAM

Approximately $4.50/kg AI or $2.05/lb AI

Liquid PAM (PAM-Calcium)

Approximately $12.00/kg AI or $5.45/lb AI

Environmental and Safety Considerations

Although still under investigation, current data indicate that PAM, formulated for agricultural erosion control (see NRCS Conservation Practice Standard – pg. 2 above), poses little or no threat to the environment and is non-toxic to humans, animals, fish, aquatic invertebrates, and plants. The 0.05% acrylamide monomer limit was established due to the neurotixicity, genotoxicity and carcinogenicity of the monomer at higher doses. The anionic forms of PAM do not interfere with the function of fish gills as can occur with other forms of PAM.

PAM is degraded in soil by cultivation, sunlight, and mechanical breakage. Because it has such a high affinity for suspended sediments and soil, very little PAM ever leaves as runoff, and if it does wash out of fields it is quickly bound to sediments in the flow or onto ditch surfaces (Lentz and Sojka, 1996).

Since PAM application can affect water infiltration, Oliver and Rei (2006) caution that vertical movement of soluble pesticides requires further investigation. However, their analysis found no increase in the infiltration of a soluble pesticide, atrazine, into the soil profile when PAM was applied.

Applicators should wear personal protection equipment as indicated on the label to limit exposure to the skin and mucous membranes. Another practical consideration is the fact that PAM spills become very slippery if wet; granular PAM spills on roadways and smooth walking surfaces should be cleaned with a dry absorbent material before an attempt is made to clean it up with water.

Summary of the Effectiveness of PAM for Mitigating Various Contaminants in Runoff

The following tables give a summary of the effectiveness of PAM to keep various pollutants from traveling into larger water bodies. The references upon which the value is based are provided in the tables.

Table 8. Runoff and Sediment

Soil Type/Location	**Irrigation Method**	**Effectiveness**	**References**
Silt loam	Furrow	94% sediment reduction 15-50% increased infiltration	Sojka et al., 2000; Sojka and Lentz, 1997; Sojka et al., 1998
	Sprinkler	70% reduction in runoff 75% reduction in soil loss into runoff	Aase et al., 1998
Sandy		Little to no reduction in runoff Minimal reduction in erosion	Sepaskhah and Bazrafshan-Jahromi, 2006
California		98% reduction in sediment in irrigation generated runoff	Fulton, 2007

Table 9. Nutrients and Microorganisms

Nutrient/Microorganism	**Effectiveness** (furrow irrigation)	**References**
NO_3	85% reduction	Entry and Sojka, 2003
Total P	90% reduction	Entry and Sojka, 2003
NH4+, NO3–, dissolved reactive phosphorus (DRP), total P, K, Ca, Mg, Fe, Mn, Cu, B, and Zn	10 to 40 fold reduction	Entry and Sojka, 2003
Total coliform bacteria (TC) and fecal coliform bacteria (FC)	30-50% reduction	Entry et al., 2003

Pesticides

Although few studies have been performed to test the effectiveness of PAM for removing pesticides from irrigation runoff, the available data indicate that PAM does reduce transport of pesticides that bind to soils (i.e. pyrethroids) in agricultural runoff. A study conducted by Oliver and Rai (2006) found that the addition of PAM to the irrigation water decreased the pesticide load moving offsite by 54% ($P < 0.05$) for endosulfan, and by 49% ($P < 0.001$) for chlorothalonil.

Figure 1. Photograph demonstrating visual difference between untreated and PAM treated runoff: left furrow treated with PAM, right furrow untreated

Figure 2. Photograph demonstrating visual difference between untreated and PAM treated runoff: water on left from untreated furrow, water on right from furrow treated with PAM

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