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Using Wetlands to Remove Microbial Pollutants from Farm Discharge Water

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On the farm, the grower is also an active steward of the land, protecting soil and water quality and supporting wildlife populations by preserving their habitat. At the same time, of course, growers must ensure that their crops are free from fecal matter contamination, which has the potential to introduce pathogens that cause foodborne illnesses. Balancing these sometimes-contradictory management objectives while maintaining the farm's financial stability is a central challenge for agricultural producers. The grower who can effectively communicate a farm's sustainability objectives and the food safety professional who is knowledgeable about key agricultural conservation practices are better prepared to engage in realistic, frank discussions about what conservation and production strategies are necessary for the farm to achieve its dual objectives of food safety and resource sustainability.

In addition to concerns about food safety, microbial pathogens are considered to be among the leading causes of water quality impairment in California agricultural watersheds (Cal EPA 2004). Within a watershed, pathogenic bacteria and protozoa from humans, livestock, wildlife, and pets can be found in runoff and can contaminate surface water bodies (Knox et al. 2007). Nonpoint sources of pollution have become the main sources of microbial pollution in waterways, with agricultural activities, including manure application to fields, confined animal operations, pastures, and rangeland grazing, being the largest contributors (Rosen 2000; Dowd, Press, and Los Huertos 2008).

Constructed and restored wetlands have been among the few water management options proposed as being available to growers to filter and improve the quality of water in agricultural runoff that contains a wide range of contaminants (O'Geen et al. 2010). Specifically, constructed wetlands have been shown to be highly effective at removing pathogens from water (Ottova, Balcarova, and Vyazal 1997; Zedler 2003). However, wetlands may also provide habitat for wildlife, including birds, livestock, deer, pigs, rodents, and amphibians, and they may in turn vector pathogens that cause human disease. These animals deposit feces and urine within the wetland, an effect that has the potential to negate any benefit from pathogen removal caused by wetland filtering (Grant et al. 2001; Collins 2004). After past outbreaks of foodborne illness caused by *E. coli* 0157:H7 borne on lettuce and spinach grown in California, some food safety guidelines have encouraged growers to reduce the presence of wildlife by minimizing non-crop vegetation, including wetlands, that could otherwise attract wildlife to farm fields growing fresh produce (Beretti and Stuart 2008; Dowd, Press, and Los Huertos 2008). In this situation, food safety guidelines may be at odds with water quality improvement measures.

Many constructed and restored wetlands in California have been built with support from the USDA-NRCS through the Environmental Quality Incentives Program (EQIP) and the Wetland Reserve Program (WRP). Under these programs, most wetland systems were initially developed to mitigate the loss of wetlands and improve wildlife habitat. A key element of the design of these systems is that they receive agricultural runoff as input flows intended to maintain the wetland's saturated conditions (figure 1). In addition to increasing wildlife habitat, the observed water quality improvements linked with these types of wetlands have made them an attractive "best management practice" for irrigated agriculture (Diaz, O'Geen, and Dahlgren 2012). Our purpose in writing this publication is to show how wetlands may be used to improve water quality in agricultural settings where pathogens are a matter of concern. In addition, we will discuss wetland design and management considerations that have the potential to maximize pathogen removal and minimize microbial contamination.

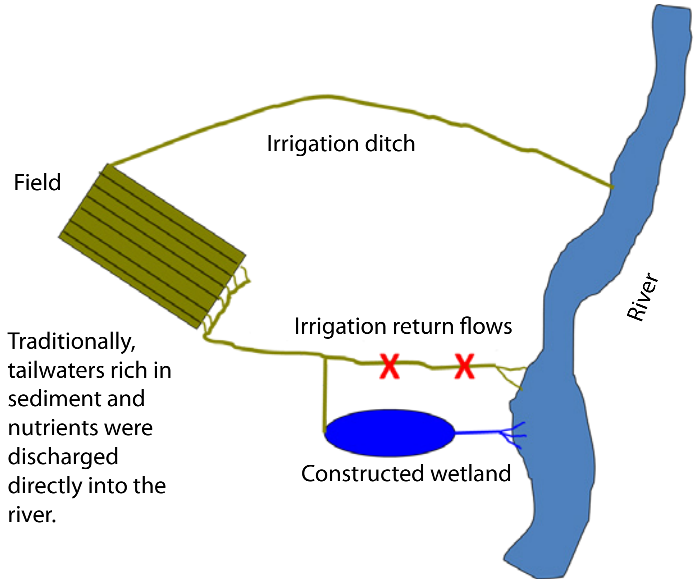

Figure 1. Schematic drawing of water flow through constructed wetlands in an agroecosystem.

Water Quality Improvement Case Study

The following case study highlights the effectiveness of wetlands as a tool to improve water quality and demonstrates the importance of specific design characteristics. A water quality assessment of seven constructed or restored surface flow-through wetlands (designated as W-1 through W-7) was conducted across the Central Valley of California. Agricultural irrigation tailwater from flood and furrow irrigation constituted the main water source for all wetlands. Agricultural land use surrounding the wetlands consisted mostly of row crops (tomatoes, melons, rice) and tree crops (nuts, stone fruits). Wetlands differed in such parameters as size, age, catchment area, vegetation type and coverage, and hydrologic residence time (HRT) (table 1). W-1 through W-4, located in the San Joaquin Valley and discharging into the San Joaquin River (SJR), were continuousflow wetlands. W-5 through W-7, situated in the Sacramento Valley and discharging into the Sacramento River (SR), were flood-pulse wetlands with a water management regime consisting of flood pulses every 2 to 3 weeks, followed by drainage for 3 to 4 days prior to the next flood pulse. W-2 and W-3 shared the same input water source, and the same was the case for W-5, W-6, and W-7. Several water quality parameters were measured at input and output locations during the growing season (March through September, 2008) to evaluate the systems' ability to improve water quality.

Table 1. Summary of wetland characteristics studied in the Central Valley of California

Wetland	**W-1**	**W-2**	**W-3**	**W-4**	**W-5**	**W-6**	**W-7**
Age (years)	1	2	2	1	3	3	3
Area (acres)	11	5.7	6.2	370	393	321	427
Contributing Farmland (acres)	3,260	800	800	4,940	—	—	—
HRT[*] (days)	2.5	0.9	1.6	11.6	15–20	15–20	15–20
Vegetation coverage (%)	5	50	50	45	60	60	60
Vegetation type	Cattail, smartweed	Smartweed	Cattail, smartweed	Cattail	Watergrass	Watergrass	Watergrass
Design/shape	Open water	Dendritic	Dendritic	Open water	Open water	Open water	Open water
Depth (feet)	3.3	3.3	2.5	2.5	2.5	2.5	2.5
Average inflow (CFS[†])	4.2	2.1	0.7	12	432	356	527

Source: Modified from Diaz et al., 2012.

[*] HRT = hydrologic residence time

[†] CFS = cubic feet per second

Table 2. Water quality contaminant load removal efficiencies

Water quality constituent	**W-1**	**W-2**	**W-3**	**W-4**	**W-5**	**W-6**	**W-7**
	- - - - - - - - - - - - - - - - - Removal efficiency (%) - - - - - - - - - - - - - - - - -						
TN[*] mg l^{-1}	19	86	55	87	– 24	– 23	8
TP[†] mg l^{-1}	24	68	23	5	– 19	– 13	– 6
TSS[‡] mg l^{-1}	43	94	89	91	41	31	43
E. coli cfu[§] 100 ml^{-1}	80	85	86	95	– 206	– 554	– 327

[*] TN = total nitrogen

[†] TP = total phosphorus

[‡] TSS = total dissolved solid

[§] cfu = colony forming units, an estimate of the number of viable bacteria

Both concentration and load are important considerations when assessing water quality constituents. *Concentration* represents the mass, weight, or volume of a constituent relative to the total volume of water. *Load* represents the cumulative mass, weight, or volume of a constituent delivered to some location.

The wetlands under study differed widely in their capacity to remove contaminants from water (table 2). The flow-through wetlands (W-1, W-2, W-3, and W-4) were most effective at reducing total nitrogen (TN), total suspended solids (TSS), and *E. coli* loads (table 2), and were moderately effective at reducing total phosphorus (TP) loads. In many instances, the flood-pulse wetlands (W-5, W-6, and W-7) were actually a source of contaminants, as indicated in table 2 by the negative numbers they show for removal efficiency.

E. coli load in outflows was significantly lower than the inflow load at all flow-through wetlands (W-1, W-2, W-3, and W-4), while the flood-pulse wetlands (W-5, W-6, and W-7) showed significant increases in *E. coli* (table 2): decreases of 80 to 95% as opposed to increases in total *E. coli* loads, respectively.

The differences in contaminant removal for flow-through versus flood-pulse wetlands can be attributed to two factors. First, the input water for the flood-pulse systems was very clean, so any introduced contaminants were readily detectable. The average *E. coli* concentration for input water was 62 cfu (colony forming units) 100 ml^{-1} in the flood-pulse wetlands, compared to over 200 cfu 100 ml^{-1} in the flow-through wetlands. Second, the overly long hydrologic residence times (HRT; i.e., water-holding times) of flood-pulse systems can allow contaminants to become more concentrated through the processes of water evaporation, leaching of nutrients from soils and organic matter, and introduction of nutrients and contaminants from feces and urine deposited by wildlife that inhabit the wetlands.

Enterococci and *E. coli* are standard federal- and state-regulated constituents used as indicators of fecal contamination in water. In the flow-through wetlands (W-1 through W-4), approximately 47 percent of water samples collected from irrigation return flows exceeded the EPA recreational contact water standard for *E. coli* of 126 cfu 100 ml^{-1} (range: 13 to 1,400 cfu 100 ml^{-1}) (figure 2). In contrast, *E. coli* concentration in wetland outflows ranged from 0 to 300 cfu 100 ml^{-1}. Following wetland treatment, 93 percent of wetland outflows met the California water quality standard for *E. coli* concentration (126 cfu 100 ml^{-1}). For enterococci, 100 percent of the input water samples exceeded the water quality standard of 33 cfu 100 ml^{-1}. Despite exceeding the water quality standard, the bacteria levels found here are very low when compared to other contaminated water sources, such as wastewater (Hench et al. 2003; Morgan et al. 2008). Although enterococci removal efficiencies ranged from 86 percent (W-1) to 94 percent (W-4), only 30 percent of the outflow enterococci concentrations met water quality standards (33 cfu 100 ml^{-1}) (figure 3). Results from this study indicate that by passing irrigation tailwater through wetlands, a grower can significantly reduce the water's pathogen concentration and load, as well as other water quality contaminants common to agricultural settings. Some water quality standards may never be met with wetland filtering alone, especially where the standards require extremely low values, as is the case for enterococci in irrigation water used on farms that grow produce that is intended to be consumed raw.

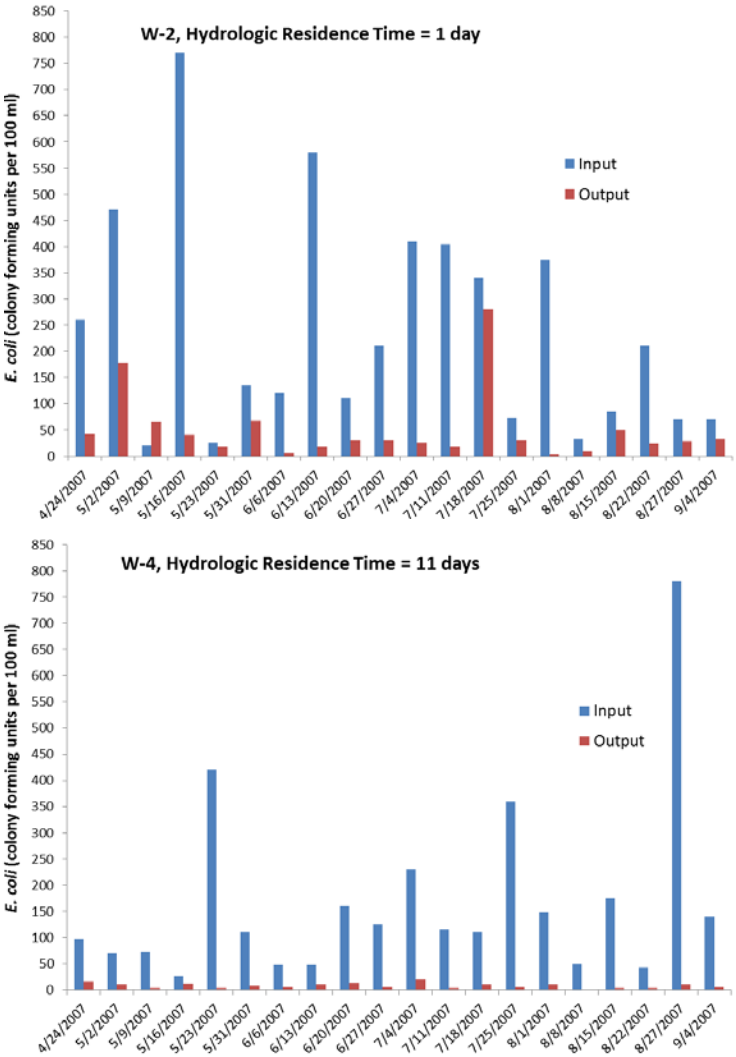

Figure 2. Comparison of input and output *E. coli* concentrations for (a) dendritic wetlands with short hydrologic residence time (HRT), approximately 1 day; and (b) an open water design with long HRT, approximately 11 days. The drinking water quality standard for *E. coli* is 126 cfu 100 ml^{-1}. From Diaz, O'Geen, and Dahlgren 2010.

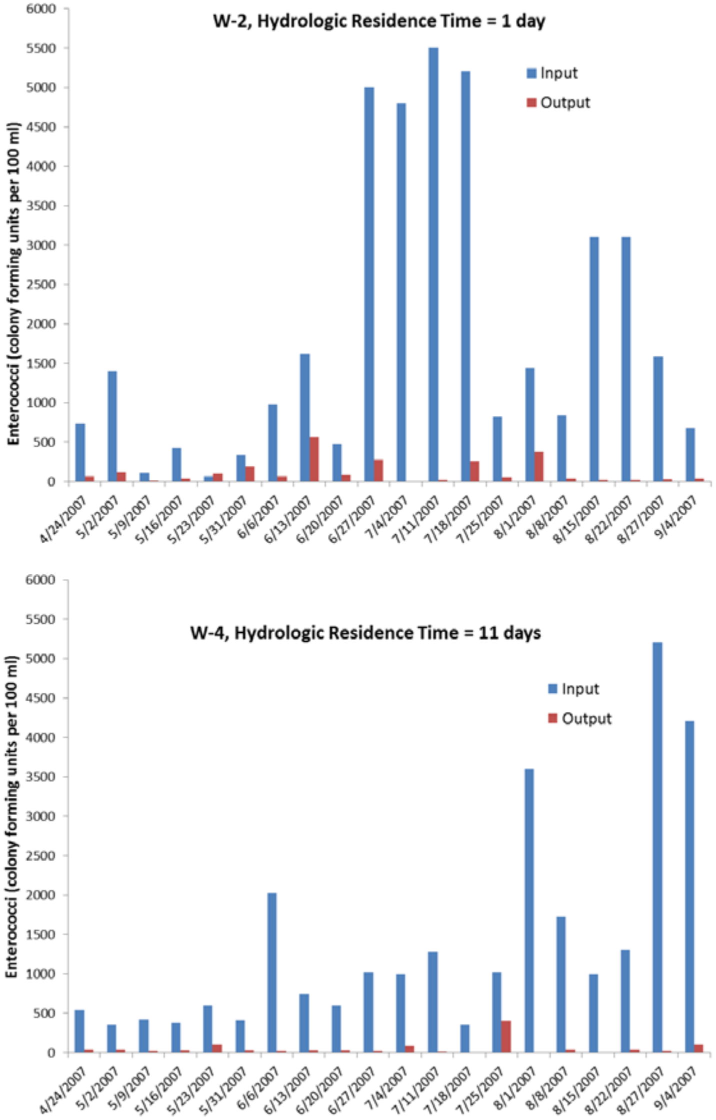

Figure 3. Comparison of input and output enterococci concentrations for (a) dendritic wetlands with short hydrologic residence time (HRT), approximately 1 day, and (b) an open water design with long HRT, approximately 11 days. The drinking water quality standard for enterococci is 33 cfu 100 ml^{-1}. From Diaz et al., 2010.

Design and Management Considerations

Wetland design and management need to be considered prior to construction and throughout the life of the system. In many cases, the natural mechanisms that promote contaminant removal or retention can be manipulated through careful design, management of hydrology, and maintenance of appropriate vegetation.

Natural mechanisms for reducing bacteria pathogens are not fully understood and have received only limited study in irrigated agriculture. Wetlands are known to act as biofilters through a combination of physical (e.g., filtration, adsorption, aggregation, biofilm trapping, and sedimentation), chemical (e.g., UV oxidative damage, biocides excreted by plants), and biological factors (e.g., predation by other microbes, enhanced survival associated with biofilms, natural die-off), all of which contribute to the reduction of bacteria numbers (Vacca et al. 2005). Where input water has a relatively low concentration (e.g., <100 cfu 100 ml^{-1}), wetland background levels are so low that water passing through the wetland may actually end up with increased pathogen concentrations (Beutel, Whritenour, and Brouillard 2013).

Sedimentation

Sedimentation is one of the primary pathogen removal mechanisms active in wetlands. Sedimentation is the physical process of particles settling in water. As high-energy input flows disperse across the wetland, the water's velocity decreases, and particles that had been suspended in the water settle to the bottom. The energy needed to support suspended particles in the water flow dissipates as the cross-sectional area of the wetland flow path increases, and vegetation reduces the water's turbulence and velocity. The rate of sedimentation is governed by particle size, particle density, water velocity and turbulence, salinity, temperature, and wetland depth. Larger pathogens tend to settle more quickly than smaller ones. The actual removal of pathogens by means of sedimentation depends on whether the pathogens are free-floating or are attached to particles. Pathogens can be attached to suspended particles such as sand, silt, clay, or organic particulates. Microbial contaminants associated with particles, especially dense, inorganic soil particles, settle out in wetlands sooner than those in the free-floating form. Studies have shown that the rate of pathogen removal is greater in wetlands where the input waters have a high sediment load (Characklis et al. 2005).

Some wetland designs are more prone to encourage wave activity, which prevents sedimentation and encourages re-suspension of settled particulates (figure 4). High wind velocities promote wave activity. Large, open-water designs are more prone to water turbulence because wind velocity increases over a large, smooth surface. Wetland vegetation can help minimize water turbulence and particle re-suspension. For example, trees planted as wind barriers surrounding the wetland decrease the amount of wind on the wetland. Emergent vegetation within the wetland can anchor sediment with its roots and can dampen the velocity of wind moving across the water surface. Dendritic wetland designs, which consist of a sinuous network of water-filled channels and small, vegetated uplands, can help reduce water turbulence associated with high winds (figure 4).

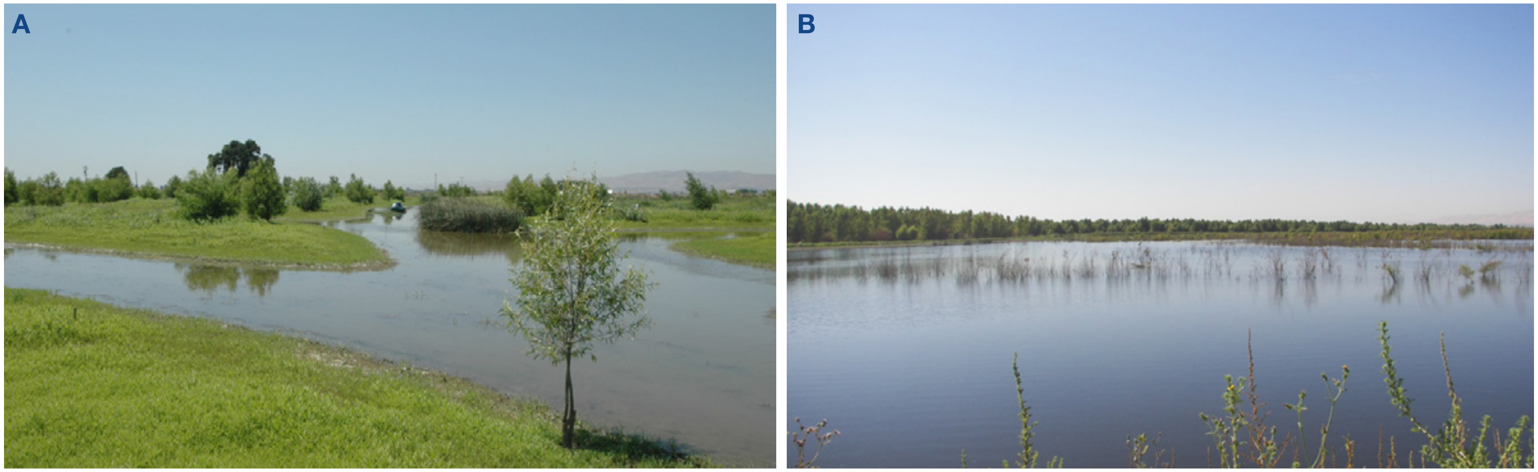

Figure 4. Examples of flow-through wetlands with (a) dendritic and (b) open water designs. Note the microtopographic highs planted with trees in the dendritic design, which will dampen wind velocity.

Vegetation

Vegetative cover has been shown to decrease sediment re-suspension. For example, Braskerud (2001) found that an increase in vegetative cover from less than 20 percent up to 50 percent reduced the rate of sediment re-suspension from 40 percent down to near zero. Wetland depth may also have an indirect effect on sediment retention. The water should be deep enough to mitigate the effect of wind velocity on the underlying soil surface, but if the water is too deep, vegetation will not be able to establish and a significant increase in re-suspension of sediment will result. Water depths between 10 and 20 inches optimize conditions for plant establishment, decreased water velocity, well-anchored soil, and a short distance for particles to fall before they can settle (Braskerud 2002).

An excess of vegetation can significantly reduce a wetland's capacity to retain *E. coli*. Maximum removal of *E. coli* occurs under high solar radiation and high temperature conditions (Whitman et al. 2004; Boutilier et al. 2009), and vegetation provides shading that can greatly reduce both UV radiation and water temperatures. While vegetation can provide favorable attachment sites for *E. coli*, a dense foliage canopy can hinder the free exchange of oxygen between the wetland and the atmosphere. This vegetation-induced barrier to free exchange of oxygen limits dissolved oxygen levels, and that in turn reduces predaceous zooplankton, further decreasing removal of microbial pathogens from the wetland environment (MacIntyre, Warner, and Slawson 2006).

Vegetation plays an important role in filtering contaminants in wetlands. The plants' uptake of pollutants, including metals and nutrients, is an important mechanism, but is not really considered a removal mechanism unless the vegetation is harvested and physically removed from the wetland. Wetland vegetation also increases the surface area of the substrate for microbial attachment and the biofilm communities that are responsible for many contaminant transformation processes. Shading from vegetation also helps reduce algae growth. However, certain types of vegetation can attract wildlife such as migrating waterfowl, which may then become a source of additional pathogens. Vegetation that serves as a food source or as roosting or nesting habitat for waterfowl may need to be reduced in some settings.

Among other important considerations for vegetation coverage in wetlands, one must include total biomass and depth features. Vegetation should provide enough biomass for nutrient uptake and adsorptive surface area purposes, but must also be managed to allow sufficient light penetration to enable natural photodegradative processes and prevent accumulation of excessive plant residues, which would prevent the export of dissolved organic carbon. One way to promote this balance is to create areas of deeper water intermixed with the shallower areas. Plants will establish more readily in the shallow areas and less so where the water is deeper. In an agricultural setting, it may be hard to establish plantings of native species within wetlands due to the large seed bank of exotic species that may be present in input waters (Kovacic et al. 2006). You can also manage the type and amount of vegetation by manipulating the timing and duration of periods of standing water in the system. In extreme instances, you can actually harvest excess biomass.

Hydrology

In addition to managing vegetation and water depth to maximize sedimentation and pathogen photodegradation, growers can also manipulate hydrology to maximize the removal of microbial pollutants in wetlands. The importance of hydrologic residence time (HRT; water-holding times) is apparent when you recognize that a longer HRT increases the exposure of bacteria to any removal processes such as sedimentation, adsorption, predation, impact of toxins from microorganisms or plants, and degradation by UV radiation (Stottmeister et al. 2003). *E. coli* concentrations have been shown to increase in runoff from irrigated pastureland when the volume of runoff is increased (Knox et al. 2007). High runoff rates increase the mobility of contaminants from fields and decrease the HRT within the wetland, thus reducing the opportunity for filtering pathogens.

Despite variations in several characteristics among the four flow-through wetlands in the case study described earlier, HRT was a consistently good predictor of *E. coli* removal efficiency. Mean removal efficiency was 69, 79, 82, and 95 percent for wetlands having mean HRTs of 0.9, 1.6, 2.5, and 11.6 days, respectively (figure 5). Remarkably, an HRT of less than a day can allow for considerable *E. coli* retention (about 70 percent), which means that a relatively small wetland area can treat runoff from a relatively large agricultural area. The relationship between removal and HRT was not so clear for enterococci (figure 5). In this case, W-1, with an HRT of 2.5 days, demonstrated a lower removal rate than W-2 or W-3, which had HRTs of 0.9 and 1.6 days, respectively (figure 5). These differences are clear evidence that different organisms can behave differently in wetlands. As discussed above, there are many parameters that can influence the environmental fate of pathogens in wetlands, including vegetation density, design, age, size, contributing area, and depth. A number of these wetland characteristics can doubtless be altered to increase bacteria removal efficiency.

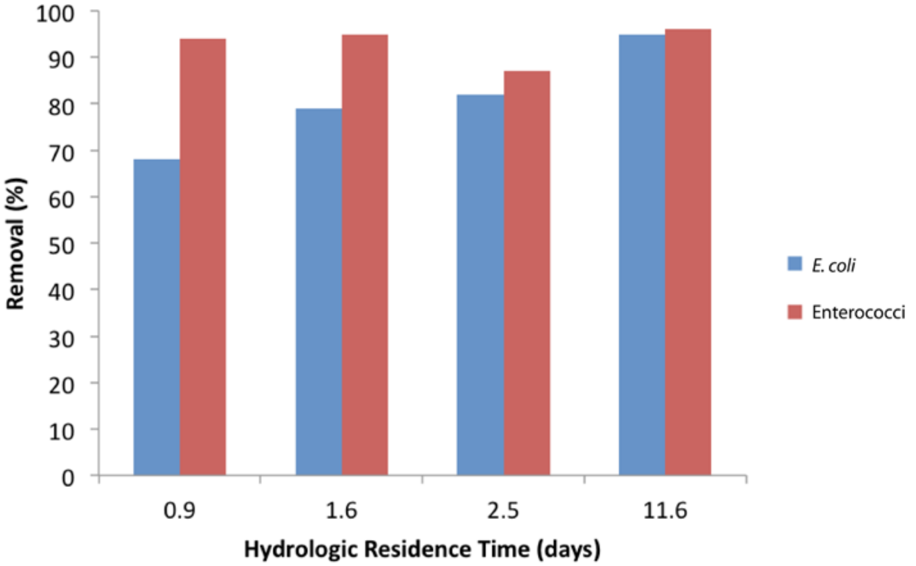

Figure 5. Pathogen concentration removal efficiency relative to hydraulic residence time (HRT).

The efficiency with which contaminants can be reduced in agricultural water as it passes through a wetland is largely dependent on the extent to which water is evenly distributed across the wetland area. A wetland's retention capacity is diminished if its design results in stagnant zones that either reduce the effective treatment area or short-circuit longer flowpaths, decreasing the HRT. Efficient wetlands come in a variety of shapes and sizes. A wetland should be wide enough to allow sufficient trapping of sediment and other particulate materials and long enough to permit sufficient residence time for nutrient removal. Most researchers agree that the surface area of a wetland should be as large as possible in order to maximize its HRT and storage capacity.

The even dispersion of water across the wetland, termed hydraulic efficiency, is largely defined by the wetland's dimensions and the relative locations of input and output channels. High hydraulic efficiency maximizes the removal of contaminants. Designs with good hydraulic efficiency have a shape that facilitates complete mixing throughout the wetland without the persistence of stagnant zones, or may incorporate barriers that achieve the same effects (figure 6).

All designs with good hydraulic efficiency have their input and output channels positioned on opposite ends of the wetland. Examples of efficient designs can include

- multiple input channels located across the width of the wetland
- upland barriers constructed to create a sinuous path across the length of the wetland
- an island that obstructs and diverts input flow to both sides of the wetland
- a submerged berm across the width of the wetland near the input, encouraging vertical mixing of the water column
- a very long, narrow design

A large wetland will require multiple inlet and outlet channels that encourage parallel flowpaths and minimize stagnant zones. Areas of contrasting water depths can also help encourage vertical mixing of water in the wetland.

Sediment traps

The sediment trap is an important design feature in settings where the input water has a high level of suspended solids (Long, Fulton, and Hanson 2010). Sediment traps are essentially small swales or ponds positioned between the source of the agricultural water and the main wetland to promote the settling of coarse particles before the water is distributed across the wetland. Sediment traps should be located in easily accessible areas where sediment can conveniently be removed on a regular basis. Incorporation of sediment traps in your design will decrease the amount of sedimentation within the wetland, lengthening the time you can go between dredgings. They also prevent the burial of germinating seedlings in the wetland and help limit channelization and short-circuiting of flowpaths.

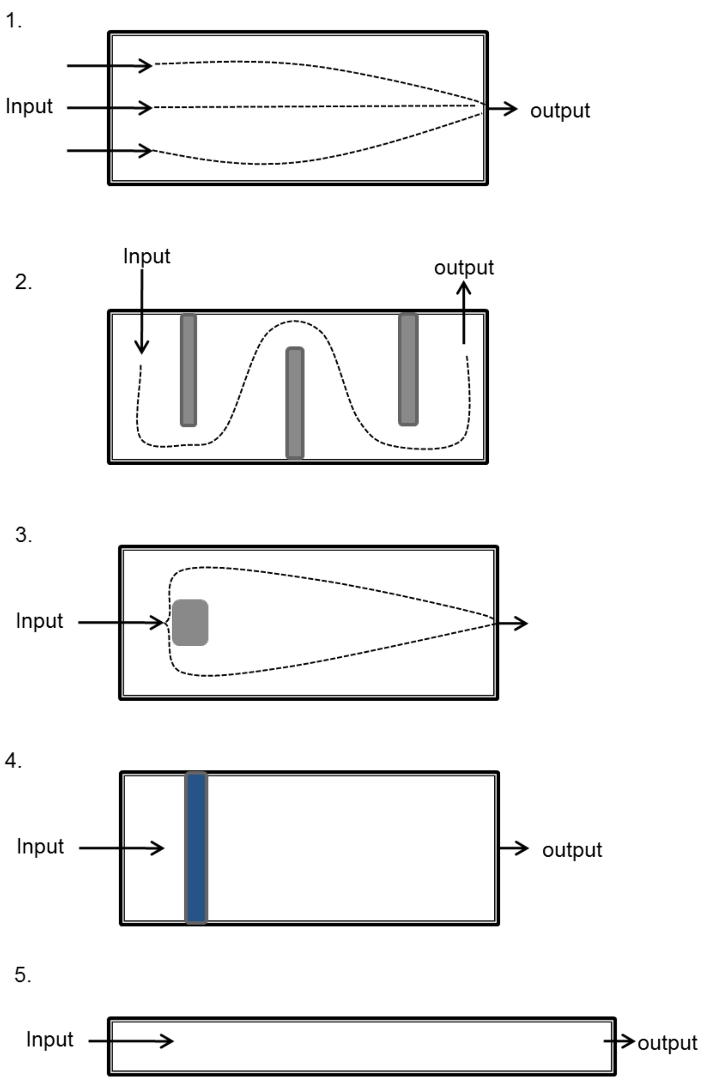

Figure 6. Hypothetical wetland designs to optimize hydraulic efficiency. Example 1 demonstrates how multiple inputs promote more even distribution of contaminants. Examples 2 and 3 show how constructed barriers (e.g., islands and peninsulas) can introduce complexity in the flowpath and encourage mixing. Example 4 depicts a submerged berm that promotes vertical mixing of the water column. A long, narrow wetland shown in example 5 can also maximize hydraulic efficiency, although this design may not be practical in agricultural settings where large volumes of water are processed. (Redrawn from Persson, Somes, and Wong 1999 and O'Geen et al. 2010.)

Sources of Contamination

Pathogen survival in wetlands

The amount of microbial pollutants in wetland soils is significantly higher than in the standing water. Bacteria survive longer in soil than in water (Howell, Coyne, and Cornelius 1996). Fecal coliforms can persist in sediments for as long as 6 weeks (Knox et al. 2007), so the degree to which sediments are deposited in a wetland has a significant effect on the degree to which bacteria are exported in effluent waters, post-wetland. The survival time for pathogens varies widely in agricultural settings, probably as a result of local differences in environmental conditions (USDA-NRCS 2012). If conditions are conducive to pathogen survival, any of a number of wetland conditions that cause the re-suspension and entrainment of sediment—e.g., high water flow pulses into wetlands, wave action, or channelization—may lead to the release of waters that contain microbial pollutants.

If you manage wetlands to allow for alternating episodes of flooding and drying, you may be able to decrease the survival of microbes in the wetland soil. In addition to desiccation associated with episodes of dry wetland soil, fluctuations in wetted surface area and depth can facilitate a diversity of biological and biogeochemical conditions that optimize wetland function and minimize the duration of pathogen survival (O'Geen et al. 2010).

Placement

There are two general options to reduce nonpoint source pollution from agriculture: on-site farm management practices that control the pollution source or limit the application of excess materials and their subsequent loss from farmlands, and off-site practices that intercept nonpoint source pollutants before they reach downstream waters. Wetlands can be used within a farmscape as either an on-site farm practice or an off-site tool, where downstream flood plains are converted to wetlands to mitigate pollution at the watershed scale. In settings where the attraction of wildlife is of concern, you may want to consider placing the wetland off-site, but at a place where it will intercept the runoff before it enters a natural water body. This may also require re-routing of the agricultural runoff into an off-site wetland.

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