

Municipal and animal waste can be treated in ponds, wetlands, and agricultural fields. The sizing of ponds, wetlands, and field application areas is based on waste characteristics and volume. Wetland and pond areas are calculated based on standard treatment times, such as 5 day hydraulic retention time, or based on decay rate equations. The decay rate constant is primarily a function of temperature. Application of animal waste to soils by solids spreading (vehicle), liquid spreading (vehicle) or through a sprinkler system requires a series of calculations: the nutrient content in the wastewater, nutrient needs of the crop, the degradation and volatilization of nutrients in storage, mineralization, denitrification, and plant uptake in soils. The rate of application by sprinklers is dependent on percent solids in the waste and soil texture. This chapter includes an NRCS example calculation of dairy waste application to cropped fields. The soil salinization hazard from animal waste is calculated from the manure salinity load. Finally, an example shows how to calculate the blended ratio of wastewater to fresh water when wastewater concentration of nitrogen exceeds the crop nitrogen requirements.

Wetlands

This section includes rate equations, biological and hydraulic loading rates, and strategies for nitrogen removal. Microbial degradation of contaminants in wetlands over time can be modeled with a first-order reaction equation.

$$\frac{dC}{dt} = -kC \tag{24.1}$$

Equation 24.1 can be integrated and solved for final concentration, C_2 .

$$C_2 = C_1 e^{-kt} \tag{24.2}$$

where

- C_2 = contaminant concentration in effluent, mg/L,
- C_1 = influent concentration, mg/L,
- k = temperature dependent rate constant, 1/days,
- t = hydraulic retention time, days.

Subsurface flow and free water surface wetlands are generally designed based on plug flow (no mixing) through the wetland. Thus, the time of reaction, T , is equal to the hydraulic detention time (HDT) of water in the wetland (the length of time that water remains in the wetland).

$$C_{out} = C_{in} e^{-kt} \tag{24.3}$$

where

- C_{out} = the contaminant concentration in the effluent, mg/L,
- C_{in} = the influent concentration, mg/L,

The rate equation can be modified to account for natural processes that may add contaminants to the flow. For example, nitrogen is continuously added to the wetland by plant decomposition, animal waste and other contributions. Thus, first-order decay equation includes the irreducible background concentration.

$$C_{out} - C^* = e^{(-kt)} (C_{in} - C^*) \tag{24.4}$$

where

- C^* = irreducible background concentration (mg/L)

The reaction rate constant is commonly based on the wetland area divided by the flow rate rather than the hydraulic detention time. This is based on the assumption of a typical average depth of water in the wetland. If a wetland

Table 24.1 Constants at 20 °C for FWS and SSF wetlands (Credit (Knight et al. 1995), Arizona Department of Environmental Quality Wetlands Design Manual)

Surface Flow (FWS)	BOD	TSS	NH ₄ ⁺	NO ₃ ⁻	TN	TP
k ₂₀ (m yr ⁻¹)	35	1000	18	35	22	12
θ _k	1.0	1.0	1.04	1.09	1.05	1.0
Irred. C ₂₀ (mg/L)	6	4.7 + .09 C ₁	0.0	0.0	1.5	0.02
θ _c	1.0	1.065	–	–	1.0	1.0
Subsurface Flow	BOD	TSS	NH ₄ ⁺	NO ₂₊₃	TN	TP
k ₂₀ (m yr ⁻¹)	180	1000	34	50	27	12
θ _k	1.0	1.0	1.04	1.09	1.05	1.0
Irred. C ₂₀ (mg/L)	6	4.7 + .09 C ₁	0.0	0.0	1.5	.02
θ _c	1.0	1.065	–	–	1.0	1.0

has a dramatically different depth than conventional wetlands, then area-based rate constants are not applicable.

$$C_{out} - C^* = e^{\left(\frac{-kA}{Q}\right)} (C_{in} - C^*) \quad (24.5)$$

where

A = wetland area, m²,
Q = flow rate, m³/yr.

The rate constant, k, is a function of temperature because microbial metabolism generally increases with temperature. The rate constant, k, is typically given for 20 °C water and then modified based on the difference between water temperature and 20 °C.

$$k = k_{20} \theta_k^{(T-20)} \quad (24.6)$$

where

k₂₀ = rate constant at 20 °C, d⁻¹
θ_k = temperature coefficient
T = Temperature, °C.

The irreducible background concentration is also a function of temperature and is modeled with a similar equation.

$$C^* = C_{20} \theta_k^{(T-20)} \quad (24.7)$$

where

C₂₀ = background concentration at 20 °C,

Reaction rate and background concentration constants for six contaminants in FWS and SSF wetlands are given in Table 24.1.

Hydraulic detention time is also the time in the reaction rate equations. It is calculated as wetland volume divided by the product of area and average depth. Subsurface (SSF) wetland volume is also a function of porosity:

$$V = Ad\phi \quad t = V/Q \quad (24.8)$$

where

A = wetland area, m²,
d = depth of water, m,
φ = porosity of gravel media,
V = wetland volume, m³.

Example 24.1 Effluent is discharged from septic tanks into a subsurface flow wetland. Wetlands area is 1,070 m². Total nitrogen in septic tank effluent is 36 mg/L. Hydraulic loading rate is 25,000 m³/yr. Water temperature in the wetland is 20 °C. Calculate total nitrogen, TN, in wetlands effluent with Eq. 24.4. Recalculate for 4 °C. Determine whether the wetland is large enough to comply with a maximum allowable TN equal to 10 mg/L in wetland effluent. Next, convert the area-based constant in Table 24.1 to a time-based constant with the assumption that the area-based constant is calibrated for a void fraction in the gravel equal to 0.33 and a depth of flow equal to 0.4 m. Then calculate effluent quality with a 5 day detention time.

Calculation of effluent concentration at 20 °C

The irreducible background concentration for total nitrogen is not temperature dependent and is a constant, 1.5 mg/L. The area-based rate constant, k₂₀, at 20 °C is 27 m/yr (Table 24.1).

$$\begin{aligned} C_{out} &= C^* + e^{\left(\frac{-kA}{Q}\right)} (C_{in} - C^*) \\ &= 1.5 + e^{\left(\frac{-27 * 1,070}{25,000}\right)} (36 - 1.5) = 12 \text{ mg/L TN} \end{aligned}$$

The wetland is inadequate because the treatment goal of 10 mg/L of total nitrogen is exceeded. Thus, the size should be increased.

Calculation of effluent concentration at 4 °C

$$\begin{aligned} k &= k_{20} \theta_k^{(T-20)} = 27 * 1.05^{(4-20)} = 12.37 \text{ m/yr} \\ C_{out} &= C^* + e^{\left(\frac{-kA}{Q}\right)} (C_{in} - C^*) = 1.5 + e^{\left(\frac{-12.37 * 1,070}{25,000}\right)} (36 - 1.5) \\ &= 22 \text{ mg/L TN} \end{aligned}$$

The wetland is even more inadequate at a lower temperature. It is not surprising that the wetland is inadequate given the fact that the hydraulic detention time is 2 days:

$$\begin{aligned} V_{cv} &= d A \theta = 0.4 \text{ m}(1,071 \text{ m}^2)(0.33) = 141 \text{ m}^3 \\ T &= V/Q = 141 \text{ m}^3/25,000 \text{ m}^3/\text{yr}(365 \text{ day / yr}) \\ &= 2 \text{ days} \end{aligned}$$

Calculate an equivalent time-based rate constant (e^{-kT}) from the area-based rate constant.

$$\begin{aligned} \frac{-k_{area}A}{Q} &= -k_{time}T = \frac{-k_{time}V_{cv}}{Q} \\ k_{time} &= \frac{k_{area}A}{V_{cv}} = \frac{k_{area}}{d\theta} = \frac{(27 \text{ m/yr})}{0.4 (0.33)} \left(\frac{1}{365 \text{ day/yr}} \right) \\ &= 0.56 \text{ d}^{-1} \end{aligned}$$

Calculate effluent TN with 5-day detention time and 20 °C ($A = 1,070 (5/2) = 2,680 \text{ m}^2$)

$$\begin{aligned} C_{out} &= C^* + e^{(-kT)}(C_{in} - C^*) = 1.5 + e^{(-5*0.56)}(36 - 1.5) \\ &= 3.6 \text{ mg/L TN} \end{aligned}$$

Calculate effluent TN with 5-day detention time and 4 °C ($A = 2,678 \text{ m}^2$)

$$\begin{aligned} k &= k_{20}\theta_k^{(T-20)} = 0.56(1.05^{(4-20)}) = 0.26 \text{ m/yr} \\ C_{out} &= C^* + e^{(-kT)}(C_{in} - C^*) = 1.5 + e^{(-5 * 0.26)}(36 - 1.5) \\ &= 11 \text{ mg/L TN} \end{aligned}$$

The 5-day detention time at 4 °C almost complies with the effluent standard of 10 mg/L.

In Table 24.1, the area-based rate constant is approximately 5 times higher in the SSF than the FWS for BOD. The increased decay rate means that SSF wetlands can have a much smaller area than FWS wetlands if the criterion is BOD treatment. FWS wetlands require approximately 20 m²/person for secondary treatment, while SSF wetlands require only 2.5 m²/person for secondary treatment. The improvement in BOD treatment is due to the filtration capacity of the gravel medium. However, the improved filtration also leads to the main problem with SSF wetlands, clogging and loss of hydraulic conductivity.

Biological and Hydraulic Loading Rates

Wetlands can be designed based on a maximum biological loading rate where loading refers to kg of contaminant (BOD₅ loading rate) per ha of wetland surface area per day. The *maximum* loading rate is calculated by estimating

the oxygen transfer capacity of the wetland vegetation. The BOD should not overwhelm the capability of the wetland to produce oxygen (EPA 1988). The BOD loading rate should also not be extremely low (reason below). The required oxygen (kg/d) to meet the total demand of the waste load can be calculated as:

$$\text{Required oxygen(kg/d)} = 1.5 \text{ BOD}_5(\text{kg/d}) \quad (24.9)$$

The available oxygen is the product of oxygen transfer rate and wetlands area.

$$\text{Available oxygen(kg/d)} = \text{TrO}_2 A \quad (24.10)$$

where

TrO_2 = oxygen transfer rate for the vegetation, kg/(ha-d)
 A = wetlands surface area, ha.

Herbaceous aquatic plants transfer oxygen at rates between 50 and 450 kg/ha/day in FWS wetlands. A typical transfer rate is 200 kg/ha-d. The BOD₅ loading rate for a wetland can be found by setting the available oxygen equal to the required oxygen for BOD removal.

$$\begin{aligned} 1.5 \text{ BOD}_5 &= (\text{TrO}_2)(A) \\ \frac{\text{BOD}_5}{A} &= \frac{200 \text{ kg/ha/d}}{1.5} = 133 \text{ kg/ha/d} \end{aligned}$$

As a safety factor, the BOD₅ oxygen load should be less than the available oxygen. Thus, the EPA (1988) recommends a maximum loading rate of 112 kg BOD₅/ha-d for FWS wetlands. In practice, hydraulic loading rates for FWS wetlands typically range from 150 to 500 m³/ha/day with a loading rate of 200 m³/ha/day resulting in the greatest treatment efficiency (EPA 1988).

The minimum acceptable BOD₅ loading rate is based on the amount of carbon required for denitrification. If inadequate carbon is available, then the microbial reaction that causes denitrification does not occur. This is also why denitrification does not take place in soils with low organic carbon.

Alternation of Aerobic and Anaerobic Treatment Zones for Nitrification and Denitrification

With high waste levels and limited land area, supplemental oxidation may be needed. One alternative is floating aquatic plant (FAP) wetlands, which have mechanical air injection and alternating aerated and nonaerated zones.

Peter Livingstone developed an innovative design with 4 anaerobic/aerobic cycles (Fig. 24.1) at the Desert Museum

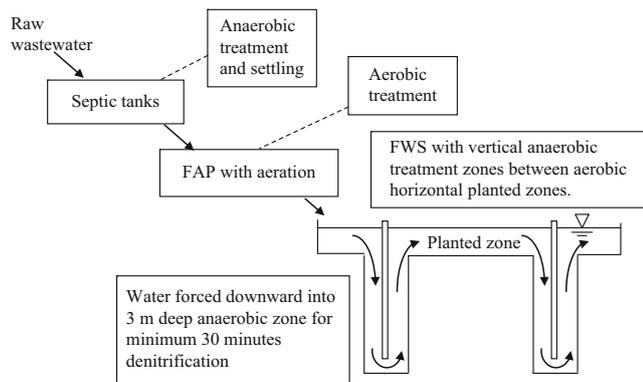


Fig. 24.1 Desert Museum wetlands in Tucson Arizona (Designed by Peter Livingstone)

in Tucson, Arizona. This wetland, with 4 vertical denitrification zones (only two are shown) has undetectable nitrogen levels at the end of the wetland; however, before the vertical zones were installed, nitrogen in effluent exceeded the acceptable discharge concentration (>10 mg/L). The vertical zones were relatively easy to install: a trench and barrier is placed across the wetland that forces the water downward into the anaerobic zone.

Water Balance in Wetlands

Evapotranspiration can vary dramatically with the seasons, and a wetland must operate in summer and winter in order to keep the plants alive. A volume balance for water flow in a wetland must be conducted in order to ensure that sufficient water is allocated to the wetland during dry periods. Seepage, evapotranspiration, and precipitation depths are multiplied by wetlands surface area to calculate rate of volume change from each of these processes.

$$\Delta d_{cv}(A) = Q_{in}t - Q_{out}t - d_{seepage}(A) - ET(A) + P(A) \quad (24.11)$$

where

Q_{in} = inflow rate, m^3/day ,

t = time, day,

Q_{out} = effluent flow rate, m^3/day ,

ΔV = change in water volume within the wetland, m^3 ,

ET = evapotranspiration, m ,

A = wetlands surface area, m^2 ,

P = depth of precipitation, m ,

$d_{seepage}$ = depth of infiltration below the wetland, m ,

Δd_{cv} = depth of water in the wetland, m .

Example 24.2 The wastewater inflow rate of the Pinetop-Lakeside wetland near Pinetop, Arizona is $1,500$ m^3/d

during summer (Table 5.2, Arizona Department of Environmental Quality manual). The area (A) of the wetland is 38 ha. The evapotranspiration rate (ET) is 1.14 cm/day in summer, and precipitation is effectively zero. Assume that the average percentage of the wetland that is filled with plant material is 3%. Neglect seepage. What is the change in water surface elevation during a 1-day period if no supplemental water is added to the wetland?

$$V_{ET} = A ET = (38 \text{ ha})(1.14 \text{ cm})(10,000 \text{ m}^2/\text{ha}) \\ (1\text{m}/100 \text{ cm}) = 4,300 \text{ m}^3$$

$$V_{inflow} = 1,500 \text{ m}^3$$

$$V_{outflow} = V_{seepage} = 0.$$

$$\Delta V_{cv} = V_{inflow} - V_{ET} = 1,500 - 4,300 = -2,800 \text{ m}^3$$

Depth change (Δd) during a 1-day period without supplemental water is ΔV_{cv} over area.

$$\Delta d = \frac{\Delta V_{cv}}{A(1 - \%plants)} = \frac{-2,800 \text{ m}^3}{380,000 \text{ m}^2(1 - 0.03)} \\ = -0.0076 \text{ m} = -0.76 \text{ cm}$$

Thus, supplemental water may be required in summer.

Waste Application to Crops

Animal Waste

Animal waste management is surprisingly important for the environment and for farm economics. Animal waste production in the United States is 130 times greater than the human waste production; a single 50,000 unit hog farm produces as much waste as the entire city of Los Angeles (Lusk 1998). Nitrogen containing compounds in animal waste are the primary water quality concern associated with animal waste (Lusk 1998). Nutrients can lead to eutrophication in streams and ultimately to large dead zones in the ocean. Many counties in the US have more nitrogen in animal waste than crop uptake capability. In this case, treatment and removal is necessary to prevent water pollution. In theory, the loop is closed if nutrients in animal waste are applied to crops, and crops take up the waste; however, misapplication of waste, volatilization of greenhouse gases, or inefficient irrigation can lead to environmental contamination.

There are numerous methods of animal waste disposal and utilization. Waste can be applied to fields as dry manure, compost, slurry, or relatively clear treated liquid. There are advantages and disadvantages associated with each method.

Untreated animal waste is hazardous and toxic to plants. Because of the extremely high contaminant load, animal waste effluent is treated for long periods in anaerobic lagoons prior to introduction into wetlands or soils. Animal

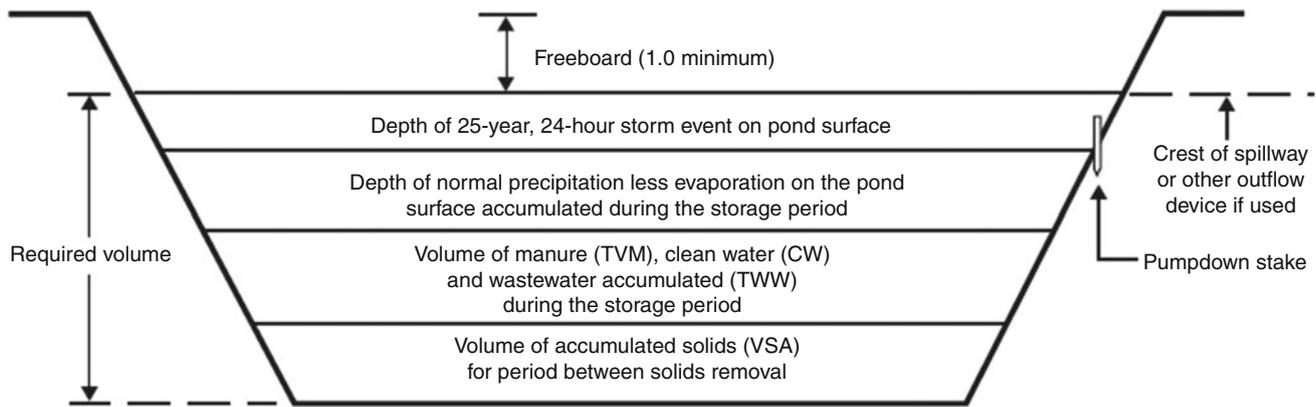


Fig. 24.2 Waste storage pond volume (without a watershed) (Credit NRCS AWMFH)

waste lagoons and wetlands require different treatment times than urban wastewater treatment facilities and wetlands because of higher contaminant concentrations in animal waste.

Animal waste has high salinity and can lead to salinization of soils and ponds. If animal waste is treated in lagoons and recirculated for flushing waste treatment facilities, the high level of evaporation in arid regions can lead to even higher salinity in lagoon water. The salinity can kill the microbes that are supposed to treat the waste.

Wet manure is typically high in ammonia and/or ammonium, which can be toxic to plants both in wetlands and in agriculture. Germination of seeds is particularly susceptible to high ammonium. Ammonium, a cation, can also block the uptake of calcium by mature plants. Thus, manure must be strategically applied, for example as a side dressing away from seeds, and in limited quantities. Another alternative is manure pretreatment to remove ammonium. Pretreatment of manure by drying in open feedlots in arid regions before application to fields, or by treatment in an anaerobic lagoon in humid regions, can reduce ammonia to acceptable levels; however, one problem with ammonia removal by drying of waste or in anaerobic lagoons is that much of the ammonia is volatilized to the atmosphere, along with methane. Ammonia and methane are potent global warming gases. Methane digestion, also known as anaerobic digestion, reduces greenhouse gas emissions from animal waste treatment. It also produces fuel for electricity generation or heating. However, many of these systems have failed, and they are generally only suitable in large animal feeding operations.

The combination of waste storage ponds or lagoons and free water surface wetlands can be effective at removing much of the nutrient load from animal waste, although volatilizing greenhouse gases into the atmosphere. The percent removal of ammonia, organic N, phosphate and BOD₅ can approach 90 % but is often in the range of 50 %

(AWMFH). The storage capacity of animal waste storage ponds (Fig. 24.2) must include the volume of sludge, manure and wastewater, as well as enough storage for the 24-hour 25-year storm plus a 1 ft (0.3 m) freeboard. Additional volume should be added if the storage pond is connected to a watershed (water can run into the pond).

Animal waste effluent wetlands areal loading rates can be calculated based on the desired effluent nitrogen concentration (AWMFH).

$$LR = 0.68(C_{out}) - 7.88 \quad (24.12)$$

where

LR = areal TN loading rate, (kg TN)/ha/day,

C_{out} = desired wetland effluent TN concentration, mg/L.

The water surface area of the wetland is the TN mass flow rate divided by the loading rate.

$$A = TN / LR \quad (24.13)$$

where

TN = total nitrogen loading rate, kg/day

A = water surface area of free water surface wetland, ha.

Although Eqs. 24.12 and 24.13 provide a general guideline for agricultural wetlands design, the specific quality of wastewaters varies, and the equations should be refined for local conditions, during the design phase if possible, but if not, during wetlands operation.

Soil type has a direct impact on the hazard level of applying manure or animal waste effluent to soils. Sandy soils with little absorption capability and high hydraulic conductivity are more likely to leach contaminants to groundwater. In addition to land application, leaking tanks, unlined lagoons,

and surface streams on farms can lead to aquifer contamination by animal waste. Once contaminants pass below the root zone, it is unlikely that they will be treated before reaching the groundwater so it is important to keep animal waste nutrients within the root zone in order to allow them to be taken up by the crop or degraded by microbes.

Composting animal waste adds cost, but compost is chemically stable and is a good soil amendment that improves soil structure. Raw manure is much more reactive, has a much higher pathogen concentration, and is more odiferous; however, if the goal is to economically add fertilizer, then manure is a better option. Compost production requires high labor input: regular turning over, adding water, and possibly adding carbon. In addition nutrients are lost during in the process. One disadvantage of applying wet manure or municipal sludge to fields is that pathogen concentrations are high. Growing edible crops is not recommended within 18 months of sludge or manure application in arid regions and within 36 months in humid regions in order to allow for pathogen reduction in soils.

The number of animals per unit land application area and the nutrient production per animal can be balanced with the crop nutrient requirement. If the nutrient load is excessive, then nutrient load can be lowered by reducing the number of animals or by extending the waste treatment time. Wetland size can be tailored to treat the wastewater to the point that it matches the nutrient load required by the farm, as shown in Eq. 24.12. Alternatively, disposal capacity can be increased by increasing land area or changing to crops that have higher nutrient requirements.

Animal waste might contain high levels of copper, zinc, and aluminum, which can be toxic to plants, humans, or animals consuming the plants. Another hazard is that animal waste often contains hormones and other chemicals that are fed to animals in order to increase production.

Animal waste that is treated in lagoons or wetlands can be dried and then applied to soil as a solid by a solids spreader (vehicle). It can also be applied as a liquid through a liquid spreader (vehicle) or through a sprinkler system. Wetlands supernatant (clear discharge with no solids), can be handled by any type of surface or sprinkler irrigation system, However, solids in wastewater limits the options, and special high-pressure pumps with chopping blades are required for pumping. Up to a solids content of 12 % (by weight) for swine and poultry manure and up to 7 % solids for cattle manure, liquid waste and slurries from lagoons or waste storage ponds can be applied to land by big gun sprinklers. Conventional sprinklers can apply cattle manure with up to 4 % solids and swine or poultry manure with up to 7 % solids.

Percent solids (wet basis) and percent moisture (wet basis) are calculated as follows:

$$P = \text{Percent solids} = \frac{\text{Dry weight}}{\text{Wet weight}}$$

$$\text{Percent moisture} = \frac{\text{Wet weight} - \text{Dry weight}}{\text{Wet weight}} \quad (24.14)$$

Waste may need to be diluted in order to pump waste through a sprinkler system. The dilution ratio is calculated as follows:

$$DR = \frac{P_0 - P_d}{P_d} \quad (24.15)$$

where

DR = dilution ratio, (volume water)/(volume manure)

P_0 = original solids content, g/g,

P_d = diluted solids content, g/g.

Example 24.3 If cattle manure has 20 % solids, then what dilution ratio is required to apply it through a sprinkler system at a solids content of 5 %. What is the ratio of water to manure?

$$DR = \frac{P_0 - P_d}{P_d} = \frac{20 - 5}{5} = 3$$

DR = (volume water)/(volume manure)

Ratio = DR → 3 parts water to 1 part manure.

When applying waste, uniform application prevents pollution and uneven distribution of nutrients in the field. Proper design of big gun spacing or traveling big guns increases uniformity. The design procedure for big gun application of lagoon effluent was described by Fulhage and Pfof from Missouri Extension (<http://extension.missouri.edu/p/EQ327>). In order to prevent runoff, the maximum application rates in Table 24.2 should not be exceeded.

Solids in irrigation water reduce infiltration rate because they clog soil pores. The reduction coefficient is the ratio of reduced infiltration with high solids content to infiltration with clean water (Table 24.3). Application rates in Table 24.2 must be multiplied by coefficients in Table 24.3 to obtain the solids adjusted application rate. Notice that the infiltration rate of fine-textured soils is not affected at all by solids in wastewater since the soil particles are smaller than the wastewater particles. Runoff to streams is more likely in sloping fields so it is especially important to ensure that infiltration rate is not exceeded in sloping fields.

Pipelines used for delivering wastewater have unique hydraulic requirements and characteristics. Average pipe velocity in all pipe sections should be kept greater than

Table 24.2 Maximum application rate, in/hr and cm/hr, as a function of total application depth (Credit NRCS AWMFH)

Total application depth (in)	0.25	0.5	0.75	1	1.25	1.5	2
Soil texture	Maximum application rate (in/hr)						
Sand	6	6	6	6	6	6	6
Loamy sand	6	6	4.83	4.22	3.86	3.62	3.32
Sandy loam	4.91	2.97	2.32	1.99	1.8	1.67	1.51
Loam	3.11	1.69	1.21	0.98	0.84	0.74	0.62
Silt loam	2.7	1.45	1.03	0.82	0.7	0.61	0.51
Sandy clay loam	1.74	0.96	0.69	0.56	0.48	0.43	0.37
Clay loam	1.27	0.68	0.48	0.39	0.33	0.29	0.24
Silty clay loam	1.09	0.57	0.4	0.32	0.26	0.23	0.19
Sandy clay	0.61	0.33	0.23	0.19	0.16	0.14	0.12
Silty clay	0.84	0.44	0.3	0.24	0.2	0.17	0.14
Clay	0.39	0.21	0.14	0.11	0.09	0.08	0.07
Total application depth (mm)	Maximum application rate (mm/hr)						
Sand	6.3	12.7	19.0	25.4	31.7	38.1	50.8
Loamy sand	15.2	15.2	15.2	15.2	15.2	15.2	15.2
Sandy loam	15.2	15.2	12.3	10.7	9.8	9.2	8.4
Loam	12.5	7.5	5.9	5.1	4.6	4.2	3.8
Silt loam	7.9	4.3	3.1	2.5	2.1	1.9	1.6
Sandy clay loam	6.9	3.7	2.6	2.1	1.8	1.5	1.3
Clay loam	4.4	2.4	1.8	1.4	1.2	1.1	0.94
Silty clay loam	3.2	1.7	1.2	0.99	0.84	0.74	0.61
Sandy clay	2.8	1.4	1.0	0.81	0.66	0.58	0.48
Silty clay	1.5	0.84	0.58	0.48	0.41	0.36	0.30
Clay	2.1	1.1	0.76	0.61	0.51	0.43	0.36
	0.99	0.53	0.36	0.28	0.23	0.20	0.18

Table 24.3 Reduction coefficient for infiltration determined by % solids (Credit NRCS AWMFH)

Soil texture	Percent solids (by wt)						
	0.5	1.0	2.0	3.0	5.0	7.0	10.0
Sand	0.88	0.55	0.31	0.22	0.13	0.10	0.07
Loamy sand	0.7	0.54	0.37	0.28	0.19	0.14	0.10
Sandy loam	0.87	0.77	0.63	0.53	0.40	0.32	0.25
Loam	0.97	0.93	0.88	0.83	0.74	0.67	0.59
Silt loam	0.98	0.95	0.91	0.87	0.81	0.75	0.68
Sandy clay loam	0.99	0.97	0.95	0.92	0.87	0.83	0.78
Clay loam	0.99	0.99	0.98	0.97	0.94	0.92	0.89
Silty clay loam	1.00	1.00	0.99	0.99	0.98	0.97	0.86
Sandy clay	1.00	1.00	1.00	1.00	0.99	0.99	0.99
Silty clay	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Clay	1.00	1.00	1.00	1.00	1.00	1.00	1.00

0.6 m/sec in order to prevent sedimentation. Friction loss is higher for slurries than for clean water (Table 24.4).

The nutrient balance calculation for application of waste to crops includes the fraction that is lost to the atmosphere in lagoons and wetlands, fraction mineralized in the soil, fraction denitrified in the soil, fraction lost to deep seepage or runoff, and fraction taken up by plants. Many of these terms have a range of values.

Nutrient retention percentages for various waste storage facilities are shown in Table 24.5. Note in the last and third to last row that a higher dilution ratio results in lower nutrient retention (higher nutrient loss) in the storage pond.

Mineralization is the process of converting organic nitrogen to nitrate. Not all organic nitrogen is mineralized immediately. Rates of mineralization for different waste sources

Table 24.4 Friction loss ratio, slurries vs. clean water (15–25 cm ID) (Credit NRCS AWMFH)

Velocity (m/s)	Percent solids					
	4	5	6	7	8	10
0.3	1.1	1.5	2.1	2.9	4	5.3
0.45	1	1.2	1.5	2.1	2.5	4
0.6	1	1	1	1.6	1.9	3.3
0.75	1	1	1	1.3	1.6	2.9
0.9	1	1	1	1.2	1.5	2.7
1.05	1	1	1	1.1	1.3	2.5
1.2	1	1	1	1	1	2.4
1.35	1	1	1	1	1	2.3
1.5	1	1	1	1	1	2.2
1.65	1	1	1	1	1	2.1
1.8	1	1	1	1	1	2
1.95	1	1	1	1	1	2
2.1	1	1	1	1	1	2

Table 24.5 Range of nutrient retention in waste treatment storage facilities (NRCS AWMFH (Table 11.5))

	Beef			Dairy			Poultry			Swine		
	N	P	K	N	P	K	N	P	K	N	P	K
Manure stored in open lot in cool, humid region	5570	7080	5570	7085	8595	8595				5570	6580	5570
Manure stored in open lot in hot, arid region	4060	7080	5570	5570	8595	8595						
Manure, liquids, and solids stored in a covered, essentially watertight structure	7085	8595	8595	7085	8595	8595				7585	8595	8595
Manure, liquids, and solids stored in an uncovered, essentially watertight structure	6075	8090	8090	6575	8090	8090				7075	8090	8090
Manure, liquids, and solids (diluted less than 50 %) held in a waste storage pond				6580	8095	8095						
Manure stored in pits beneath slatted floor	7085	8595	8595	7085	9095	9095	8090	9095	9095	7085	9095	9095
Manure treated in anaerobic lagoon or stored in waste storage pond after being diluted more than 50 %	2035	3550	5065	2035	3550	5065	2030	3550	5060	2030	3550	5060

are given in Table 24.6. Rate of degradation affects the amount of N available to the crop.

Nitrogen is lost by ammonia volatilization to the atmosphere if manure or animal waste effluent is applied to soil surface. The percent loss is a function of the type of application system, length of time that waste remains on the soil surface, temperature of the soil, and moisture content of the soil. For sprinkler application, approximately 25 % of nitrogen is volatilized (Table 24.7).

Denitrification (conversion of nitrate to atmospheric nitrogen by microorganisms) requires a carbon source. Thus, soils low in carbon have low denitrification rates. Denitrifying organisms have higher growth rates (denitrification rates) in anaerobic soils. Denitrification rates are greatest in organic (high carbon) poorly drained (anaerobic) soils. Denitrification rates per year as a function of drainage

class and organic matter content are shown in Table 24.8. No-till fields have higher denitrification rates so the AWMFH recommends using one class wetter drainage for those fields. For manure N, double all values. For tile drained (subsurface drainage) soils, use one class better drainage. For irrigation or humid climates, use values at upper end of the range. For arid or semiarid non-irrigated sites, use values at lower end of the range. For soils with a compacted, very low permeability layer below plow depth, but above 1.2 m depth, use one class wetter drainage.

The leaching index, as defined by the NRCS, is the depth of water (inches) leached below the root zone. This index has been correlated with the percent of inorganic N (NO_3^-) that is leached below the soil root zone. The percent leaching losses for leaching indexes of <2, 2–10, and >10 are 5 %, 10 %, and 15 %, respectively (AWMFH). Higher leaching

Table 24.6 Mineralization rates in soils for wastes from different animal waste treatment facilities (Credit NRCS AWMFH)

	Nitrogen			Phosphorus			Potassium		
	Years after initial application								
	1	2	3	1	2	3	1	2	3
Fresh poultry manure	90	92	93	80	88	93	85	93	98
Fresh swine or cattle manure	75	79	81	80	88	93	85	93	98
Layer manure from pit storage	80	82	83	80	88	93	85	93	98
Swine or cattle manure stored in covered storage	65	70	73	75	85	90	80	88	93
Swine or cattle manure stored in open structure or pond (<50 % dil)	60	66	68	75	85	90	80	88	93
Cattle manure with bedding stored in roofed area	60	66	68	75	85	90	80	88	93
Effluent from lagoon or diluted waste storage pond (>50 % dilution)	40	46	49	75	85	90	80	88	93
Manure stored in open lot, cool-humid	50	55	57	80	88	93	85	93	98
Manure stored in open lot, hot-arid	45	50	53	75	85	90	80	88	93

Table 24.7 Percent of nitrogen in applied manure still potentially available to the soil after surface volatilization (Willrich, 1974) (Credit NRCS AWMFH)

	Percent of nutrients retained		
	Warm dry	Warm wet	Cool wet
Injection	95		
Sprinkler	75		
Days between application by truck and incorporation			
1	70	80	100
4	60	70	95
7 or more	50	60	90

Table 24.8 Approximate N denitrification rates for various soils. Percent of inorganic N denitrified (Credit NRCS AWMFH from Meisinger and Randall (1991))

Soil organic matter content (%)	Soil drainage classification				
	Excessively well drained	Well drained	Moderately well drained	Somewhat poorly drained	Poorly drained
<2	2–4	3–9	24–14	6–20	10–30
2–5	3–9	24–16	6–20	10–25	15–45
>5	24–12	6–20	10–25	15–35	25–55

rates result in higher N leaching. Application timing influences the depth leached; for example, application of waste or fertilizer just before spring rains or heavy irrigation would result in maximum nutrient loss.

The ratio of nutrients (N, P, and K) in manure is not the same as the ratio of N, P, and K requirements of plants: Phosphorous is generally overapplied if the manure application is based on supplying the N requirement. Overapplication of phosphorous leads to environmental contamination in some regions; in this case, waste should not be applied based on the phosphorous requirement. The potential for phosphorous pollution is greatest an acidic soils and when there are adjacent water bodies. Phosphorous contamination is generally not a potential hazard in arid regions because soils are alkaline, and there are no adjacent river bodies; thus, the waste application rate can be solely based on the N

requirement. Worksheets are available from the NRCS that specify whether waste application should be based on nitrogen, phosphorous, or potassium.

Example 24.4 This example is from *NRCS AWMFH*, but it has been converted to metric units.

Given: A dairy farm has 200 lactating dairy cows in Central Wisconsin. Average mass/cow is 500 kg. The N, P, and K nutrient loads per cow are 0.45-, 0.07-, and 0.26-kg/d/1000 kg, respectively. The wastewater from the milking house effluent has N, P, and K concentrations equal to 200-, 100-, and 300-mg/L, respectively. All milking house – milking parlor waste and manure are added to an anaerobic waste storage pond. The bottom of the pond dimensions are 18 × 60 m and the maximum operating depth is 3.6 m. Side slopes are 2:1 (2 horizontal by 1 vertical). The 25-year,

224-hour storm is 15 cm. Milking parlor + milking house wastewater volume = 19 L/cow/day. No runoff water from holding areas or adjoining fields is allowed to run into the pond. Mean annual precipitation is 81 cm, annual evaporation from the pond surface is 30 cm. Dilution of manure by rainfall and milk house and milk parlor cleaning water is approximately 50 %. The climate has moderate rainfall and humidity. Phosphorous pollution is a hazard in the region.

Manure has been applied for several years every spring and is incorporated into the soil by plowing within 1 day of application.

Soils are moderately well-drained silt loams and have a leaching index of 6, which means that 15 cm (6 in.) percolates below the root zone. The organic matter content is 3 %. The rock fraction is 10 %. The soils are subject to frequent flooding. Soil slopes range up to 10 %.

The crop is corn, with a rooting depth of 1.5 m. Required yearly nutrient additions for crop growth (grain corn) are 132 kg/ha nitrogen (N), 52 kg/ha phosphorous (P_2O_5), and 39 kg/ha potassium (K_2O). Manure is applied by truck in spring just before planting when soil is wet. Soil temperature is between warm and cool (Table 24.7) but closer to cool (needed for denitrification rate calculation)

Required: Calculate manure and wastewater application rates for truck application and wastewater application rate for sprinkler application.

Answer the following questions:

1. What is the required application rate?
2. Estimate the land area required for maximum nutrient utilization.
3. What is the application rate in metric tons per hectare for the area that would provide maximum nutrient utilization?
4. For an irrigation system design, determine the total depth of wastewater application based on nitrogen requirements and for maximum nutrient utilization.

Solution:

Step 1. Estimate the total nutrients (NPK) in the excreted manure.

Annual nutrient load in excreted manure (rates from Table 2.6)

$$N = \frac{(200 \text{ cows})(500 \text{ kg/cow})(0.45 \text{ kg/d}) (365 \text{ d/yr})}{1,000 \text{ kg}} = 16,400 \text{ kg}$$

$$P = \frac{(200 \text{ cows})(500 \text{ kg/cow}) (0.07 \text{ kg/d}) (365 \text{ d/yr})}{1,000 \text{ kg}} = 2,550 \text{ kg}$$

$$K = \frac{(200 \text{ cows})(500 \text{ kg/cow}) (0.26 \text{ kg/d}) (365 \text{ d/yr})}{1,000 \text{ kg}} = 9,500 \text{ kg}$$

Step 2. Calculate annual nutrient load in the wastewater

This waste calculation includes some of the manure (as excreted) from the previous calculation because it dissolves in the water; thus, the amount of manure applied

will be slightly overestimated. Annual nutrient load added to wastewater:

$$N = (200 \text{ cows}) (19 \text{ L/d/cow}) (200 \text{ mg/L}) (10^{-6} \text{ kg/mg}) (365 \text{ d}) = 277 \text{ kg}$$

$$P = (200 \text{ cows}) (19 \text{ L/d/cow}) (100 \text{ mg/L}) (10^{-6} \text{ kg/mg}) (365 \text{ d}) = 138 \text{ kg}$$

$$K = (300 \text{ cows}) (19 \text{ L/d/cow}) (300 \text{ mg/L}) (10^{-6} \text{ kg/mg}) (365 \text{ d}) = 416 \text{ kg}$$

Total nutrients produced:

$$\begin{aligned} \text{Total N} &= 16,400 \text{ kg} + 277 \text{ kg} = 16,700 \text{ kg} \\ \text{Total P} &= 2,550 \text{ kg} + 138 \text{ kg} = 2,700 \text{ kg} \\ \text{Total K} &= 9,500 \text{ kg} + 416 \text{ kg} = 9,900 \text{ kg} \end{aligned}$$

Fertilizer requirements for crops are reported as the oxidized form of potassium (K_2O) and phosphorous (P_2O_5) and the elemental form for N. Convert P and K to the form used in crop requirement calculations. Elemental P is multiplied by 2.29, and element K is multiplied by 1.21 to calculate the amount of the oxidized forms of P and K.

$$\begin{aligned} \text{Total N} &= 16,700 \text{ kg} \\ \text{Total P as } P_2O_5 &= 2.29(2,700 \text{ kg}) = 6,200 \text{ kg} \\ \text{Total K as } K_2O &= 1.21(9,900 \text{ kg}) = 12,000 \text{ kg} \end{aligned}$$

Step 3. Subtract nutrients lost during storage.

The nutrients are held in a waste storage pond with 50 % dilution. From Table 24.5, use the maximum nutrient depletion for the waste storage pond (65 %, 80 %, and 80 % retained for N, P, and K, respectively) since the dilution (50 %) is on the high side for the low dilution category (<50 %) in Table 24.5.

$$\begin{aligned} \text{Nutrients after storage losses} \\ &= (\text{fraction retained})(\text{production}) \end{aligned}$$

$$\begin{aligned} N &= 0.65(16,700) = 10,900 \text{ kg} \\ P_2O_5 &= 0.8(6,200) = 4,960 \text{ kg} \\ K_2O &= 0.8(12,000) = 9,600 \text{ kg} \end{aligned}$$

Step 4. Determine the plant available nutrients gained by mineralization in the soil.

Mineralization rates in soil are 55 %, 90 % and 93 % (Table 24.6) for nitrogen, phosphorous, and potassium, respectively for the third year in a waste storage pond. Phosphorous and potassium values are for both >50 % and <50 % waste storage ponds, and nitrogen is an intermediate value between 49 % (>50 % dilution) and 68 % (<50 % dilution).

Nutrients available to plant = (fraction)(application rate)

$$\begin{aligned} N &= 0.55(10,900) = 6,000 \text{ kg} \\ P_2O_5 &= 0.9(4,960) = 4,500 \text{ kg} \\ K_2O &= 0.93(9,600) = 8,900 \text{ kg} \end{aligned}$$

Step 5. What are the plant nutrient requirements? This data is available from farmers, extension personnel, crop advisors, seed companies, or fertilizer companies.

$$\begin{aligned}N_{\text{-plant}} &= 132 \text{ kg/ha} \\P_2O_5\text{-plant} &= 52 \text{ kg/ha} \\K_2O\text{-plant} &= 39 \text{ kg/ha}\end{aligned}$$

Adjust the plant N requirement based on denitrification, leaching, and volatilization. We have already adjusted the waste N loading rate mineralization rate under step 4. Thus, mineralization is ignored under step 5.

Add denitrification losses to the plant nitrogen requirement.

From Table 24.7, a moderately well drained soil with an organic matter content of 3 % has an annual denitrification rate between 6 % and 20 %. Because the climate is moderate, estimate the midpoint of this range, 13 %. The values in Table 24.7 must be doubled for manure application so estimate the denitrification rate as 26 %. The plant nitrogen requirement is 132 kg/ha so the field nitrogen required is

$$N_{\text{-required-denitrification}} = 132 \text{ kg/ha}/0.74 = 178 \text{ kg/ha}$$

Add leaching losses to the plant nitrogen requirement

The plant nitrogen requirement must be increased to replace anticipated leaching losses. A leaching index of 6 (6 inches of annual percolation below the root zone), results in an annual nitrate loss of 10 %.

$$N_{\text{-required-denitrification and leaching}} = 178 \text{ kg/ha}/0.9 = 200 \text{ kg/ha}$$

Add application (volatilization) losses to plant nitrogen requirement.

Because the manure will be incorporated within 1 day, the expected nitrogen retention after volatilization is between 80 % (warm wet) and 100 % (cool wet), but since soil is closer to cool than warm, estimate percent retained as 95 %

$$\begin{aligned}N_{\text{-required-denitrification, leaching, and volatilization}} \\= 200 \text{ kg/ha}/0.95 = 210 \text{ kg/ha}\end{aligned}$$

The answer to question 1 is that the required application rate is

$$\begin{aligned}N_{\text{-plant}} &= 210 \text{ kg / ha} \\P_2O_5\text{-plant} &= 52 \text{ kg / ha} \\K_2O\text{-plant} &= 39 \text{ kg / ha}\end{aligned}$$

Step 6. Compute the field area to which manure can be applied.

First, try calculating the required land area using the nitrogen requirement.

$$\begin{aligned}\text{Area} &= (6,000 \text{ kg/year N})/(210 \text{ kg/ha N}) = 29 \text{ ha} \\&= 72 \text{ acres}\end{aligned}$$

Calculate the application rate of P and K with 29 ha application area

$$\begin{aligned}\text{Application rate } P_2O_5 &= 4,500 \text{ kg}/29 \text{ ha} = 155 \text{ kg/ha} \\ \text{Application rate } K_2O &= 8,900 \text{ kg}/29 \text{ ha} = 308 \text{ kg/ha}\end{aligned}$$

Thus, application rate of phosphorous is 3 times greater than plant requirement and application rate of potassium is 8 times greater than plant nutrient requirements, if application rate is based on nitrogen.

For maximum nutrient utilization and also to prevent phosphorous pollution, calculate the land application area based on the potassium requirement, and add other nutrients with fertilizer.

$$\begin{aligned}\text{Area} &= (8,900 \text{ kg/year } K_2O)/(39 \text{ kg/ha } K_2O) \\ &= 228 \text{ ha} = 560 \text{ acres}\end{aligned}$$

In some cases, manure may be overapplied with respect to potassium and phosphorous if the risk of pollution by these nutrients due to overapplication is low. That is not the case here. In this case, only 13 % of the N requirement is applied (29/228) in manure.

Step 7a. Calculate the application rate and volume for truck application. Truck applies both wastewater and manure. First calculate the pond volume.

The waste storage pond contains the manure produced by the 200 cows plus the milk parlor wastewater. Precipitation and evaporation must be considered to obtain the total volume of stored material.

Manure excreted per day = 81 L/day/1,000 kg (Table 2.6).

$$\begin{aligned}\text{Volume manure/year} &= \frac{(81 \text{ L/d})(200 \text{ cows})(500 \text{ kg/cow})(365)}{1,000 \text{ kg}} \\ &= 3,000,000 \text{ L/year}\end{aligned}$$

$$\begin{aligned}\text{Volume wastewater/year} &= 19 \text{ L/day/cow} * 200 \text{ cows} * 365 \\ &= 1,400,000 \text{ L/year}\end{aligned}$$

Volume of water added by precipitation

The working depth of the pond is 3.6 m. This depth includes the expected precipitation – evaporation. An additional safety factor should be added, which includes the expected 25-year 224-hour storm + 0.3 m freeboard. The 25 year 24 hour storm is 0.15 m. Thus, the distance from the bottom of the pond to the top is 3.6 m + 0.3 + 0.15 = 4.05 m.

With 2:1 side slopes, the pond surface dimensions are calculated.

$$\begin{aligned}2(4.05 \text{ m}) + 60 \text{ m} &= 68 \text{ m} \\ 2(4.05 \text{ m}) + 18 \text{ m} &= 26 \text{ m}\end{aligned}$$

Thus, volume of water added by precipitation is

$$\begin{aligned} & (\text{Precipitation})(\text{Pond area at top of pond}) \\ & = 68 \text{ m}(26 \text{ m})(0.81 \text{ m})(1,000) = 1,430,000 \text{ L} \end{aligned}$$

The volume of water lost to evaporation is calculated based on the average working pond area. Maximum working depth is 3.6 m so average depth is 1.8 m.

$$\begin{aligned} 2(1.8 \text{ m}) + 60 \text{ m} & = 64 \text{ m} \\ 2(1.8 \text{ m}) + 18 \text{ m} & = 22 \text{ m} \end{aligned}$$

Thus, volume of water lost to evaporation is

$$\begin{aligned} & (\text{Evaporation rate})(\text{Pond area at mid depth}) \\ & = 64 \text{ m} \times 22 \text{ m}(0.3 \text{ m})(1,000) = 420,000 \text{ L} \end{aligned}$$

Total water added to the pond per year (precipitation + wastewater volume – evap.) is

$$1,400,000 + 1,430,000 - 420,000 = 2,400,000 \text{ L}$$

The dilution ratio is (volume water)/(volume water + manure)

$$2,400,000 / (2,400,000 + 3,000,000) = 44\%$$

The manure, as excreted, contains 12.5 % solids. The percent solids of the diluted wastewater is

$$\begin{aligned} & (\text{Original solids content})(\text{dilution ratio}) \\ & (12.5\%)(2,400,000 \text{ L} / (3,000,000 \text{ L} + 2,400,000 \text{ L})) \\ & = 5.5\% \text{ solids.} \end{aligned}$$

The density of dairy manure with 7 % solids is 0.96 kg/L (manure bulk density can be found by weighing a known volume of manure).

$$\begin{aligned} & \text{The mass of the stored material is } (0.96 \text{ kg/L}) \\ & (5,400,000 \text{ L}) = 5,200,000 \text{ kg} = 5,200 \text{ metric tons.} \\ & \text{The application rate is } 5,200 \text{ metric tons}/228 \text{ ha} \\ & = 23 \text{ metric tons/ha.} \end{aligned}$$

The volume of manure per ha is found by dividing by the bulk density.

$$23 \text{ metric tons/ha} / 0.96 = 24 \text{ m}^3/\text{ha.}$$

Step 7b. Application of waste by sprinklers (calculated based on N and K)

For application of waste by sprinklers, the nitrogen requirement should be recalculated based on surface volatilization expected from sprinkler application (Table 24.7).

$$\begin{aligned} & N_{\text{required-denitrification, leaching, and volatilization}} \\ & = 200 \text{ kg/ha} / 0.75 = 267 \text{ kg/ha} \end{aligned}$$

Leaching and denitrification may also increase under sprinkler irrigation because of possible addition of more water and wetter soil. However, those possible losses are ignored here. Use the N mass/year after mineralization is accounted for (6,000 kg/yr N).

$$\begin{aligned} & \text{Area for full nitrogen application} \\ & = (6,000 \text{ kg/year N}) / (267 \text{ kg/ha N}) = 22 \text{ ha} \\ & = 55 \text{ acres} \end{aligned}$$

Dilute the manure such that total solids is 4 % in order to apply dairy manure through the irrigation equipment,

$$DR = \frac{P_0 - P_d}{P_d} = \frac{7 - 4}{4} = 0.75$$

The volume of combined manure and wastewater in the waste storage pond after rainfall and evaporation is 5,400,000 L. The required addition of water to reduce the solids ratio to 4 % is the product of 5,400,000 and the DR.

$$\begin{aligned} & \text{Volume dilution water/volume original wastewater} = 0.75 \\ & \text{Volume of added water} = 0.75(5,400,000 \text{ L}) = 4,000,000 \text{ L} \end{aligned}$$

The total volume of water to be applied to the field is 5,400,000 + 4,000,000 L = 9,400,000 L

The depth of water to be applied (ponded depth) to the field is the volume/area. If the application rate is based on the potassium requirement, then the area of application should be 228 ha (2,280,000 m²). The depth applied is volume/area.

$$\begin{aligned} \text{Depth applied} & = \text{Volume/Area} = 9,400,000 / 2,280,000 \\ & = 0.0042 \text{ m} = 0.4 \text{ cm.} \end{aligned}$$

Check the solution. The concentration of K₂O in the wastewater is 8,900 kg/9,400 m³ ~ 1 kg/m³. The volume applied to a hectare with a 0.4 cm application depth (0.004 m) is

$$\begin{aligned} & 1 \text{ kg/m}^3 * 0.004 \text{ m} * 10,000 \text{ m}^2/\text{ha} \\ & = 40 \text{ kg K}_2\text{O/ha}(\text{correct}) \end{aligned}$$

If the rate was calculated based on the nitrogen requirement, then the area of application would be

$$\begin{aligned} \text{Area} & = (6,000 \text{ kg/year N}) / (267 \text{ kg/ha N}) = 22.5 \text{ ha} \\ & = 225,000 \text{ m}^2 \end{aligned}$$

The calculated depth of application for nitrogen would be

$$\begin{aligned} \text{Depth applied} & = \text{Volume/Area} = 9,400,000 / 225,000 \\ & = 0.042 \text{ m} = 4 \text{ cm.} \end{aligned}$$

Thus, 10 times greater depth is applied with nitrogen if the rate is based on the nitrogen requirement. In this case, based

on Table 24.2, the maximum application rate by sprinklers would be 1.8 mm/hr with a total application depth of 4 cm on silt loam soil. With 4 % solids in irrigation water, the infiltration rate is 0.85 times as great as it would be for clear water on silt loam soil (Table 24.3). This is between the 3 % and 5 % values. Thus, the maximum application rate is $1.8 \times 0.85 = 1.5$ mm/hr. The sprinkler system should be designed to apply water at no more than 1.5 mm/hr if the entire depth is applied at one time.

Calculation of Salinity Load from Animal Waste

Animal waste carries a high salt load. Wastewater salinity in storage ponds can range up to 12 dS/m or even higher with recirculating systems. Farmers in arid regions have found that they must limit the application of manure to fields in order to avoid soil salinization.

The salinity level in manure and wastewater depends on the original concentration of salinity in the manure, the amount of wash water, and the depths of precipitation and evaporation. There is a wide range of salinity levels in manure. Average and extreme salinity levels of manures tested in Colorado are shown in Table 24.9. Manure salinity can vary depending on the level of salinity in feed and other factors. Because of the wide range of salinity levels in manure and other wastes, the EC or concentration of ions should be tested when calculating the maximum allowable waste application rate with respect to salinity. Even on a single farm, researchers have found that 20 to 40 samples must be collected in order to adequately characterize the average salinity in manure. Field management practices such as leaching and crop drought tolerance (salinity tolerance) also determine the maximum waste application rate.

Total salinity percentage can be estimated based on the percentages of the major cations (NRCS AWMFH) as specified in Table 24.11. The justification for Eq. 24.16 is that the cations comprise half of the total salinity: the other half is anions.

$$\begin{aligned} \% \text{salts} &= 2(\%K + \%Ca + \%Na + \%Mg) \text{ (by mass in dry manure)} \\ & \quad (24.16) \end{aligned}$$

Recommended manure application rates depend on the crop and the climatic region (Table 24.10). Dryland application rates recommendations can be almost 10 times less than warm irrigated regions. This assumes that irrigation will be used to leach salts from the soil. Typical cation concentrations in different manures are listed in Table 24.11.

Example 24.5 Calculate the salinity in the waste storage pond of Example 24.4, and calculate the salinity added to the field (kg/ha) if 0.4 cm is applied by sprinkler irrigation. Use cation concentrations from Table 24.11.

The total percentage of salinity in dry dairy manure is calculated with Eq. 24.16 using the cation concentrations specified for dairy manure in Table 24.11.

$$\begin{aligned} \% \text{salts} &= 2(\%K + \%Ca + \%Na + \%Mg) \text{ (by mass in dry manure)} \\ \% \text{salts} &= 2(2.86 + 1.2 + 0.47 + 0.55) = 2(5.08) = 10.16\% \\ &= 0.10 \text{ kg/kg} \end{aligned}$$

Fresh dairy manure has a solids content of 12.5 %. Thus, multiply by 0.125 to find mass of salts in wet manure.

$$\begin{aligned} (0.1016 \text{ kg salts/kg solids})(0.125 \text{ kg solids/kg manure}) \\ = 0.0127 \text{ kg salts / kg manure} \end{aligned}$$

Lactating dairy cows produce 80 kg/d/1,000 kg manure

$$\begin{aligned} \text{Mass manure/year} &= \frac{(200 \text{ cows})(500 \text{ kg/cow})(80 \text{ kg/d})(365 \text{ d})}{1,000 \text{ kg}} \\ &= 2,920,000 \text{ kg manure} \end{aligned}$$

Mass of salts produced per year

$$\begin{aligned} (2,920,000 \text{ kg manure})(0.0127 \text{ kg salts/kg manure}) \\ = 37,000 \text{ kg salts} \end{aligned}$$

Volume of manure produced per year

$$\begin{aligned} \text{Volume manure/year} &= \frac{(200 \text{ cows})(500 \text{ kg/cow})(81 \text{ L/d})(365 \text{ d})}{1,000 \text{ kg}} \\ &= 2,960,000 \text{ L manure} \end{aligned}$$

Calculate the concentration of salts in fresh manure

$$\begin{aligned} (37,000 \text{ kg salts})(1 \times 10^6 \text{ mg/kg}) / 2,960,000 \text{ L manure} \\ = 12,500 \text{ mg/L} \end{aligned}$$

The volume of manure is diluted by 2,400,000 L as precipitation and washwater. Calculate the diluted concentration.

$$\begin{aligned} (12,500 \text{ mg/L})(2,400,000 \text{ L}) / (3,000,000 \text{ L} + 2,400,000 \text{ L}) \\ = 5,600 \text{ mg/L} = 0.0056 \text{ kg/L} \end{aligned}$$

The depth of water application is 0.4 cm so $(0.004 \text{ m})(10,000 \text{ m}^2/\text{ha}) = 40 \text{ m}^3$ is applied to the field. Thus, the rate of salt application is $(40 \text{ m}^3)(1,000 \text{ L/m}^3)(0.0056 \text{ kg/L}) = 224 \text{ kg/ha}$.

Table 24.9 Salinity levels for fresh manure (Credit Colorado State Extension Service)

Manure source	Average EC dS/m	Minimum	Maximum
Beef	28.2	8.4	42.5
Horse	6.2	3.3	10.2
Sheep	23.4	9.4	42.8
Chicken	23.7	16	40.7
Dairy	18.8	9	29.5
Llama	5.5	4.1	6.9
Hog	34.8	34.8	34.8
Dairy compost	24.5	12.8	43.6
Turkey compost	35.8	2.4	42.2

Table 24.10 Recommended animal manure application rates (dry rate basis) on cultivated land. Source: Fuller and Warrick (1985)

Region	Optimum	Maximum loading rate (metric tons)
Warm irrigated (arid) regions Livestock manure Poultry manure	324–56 t/ha 11–22 t/ha	80 t/ha (to salt tolerant crops)
Cold irrigated (arid) regions Livestock manure Poultry manure	324–45 t/ha 9–20 t/ha	50 t/ha (to salt tolerant crops)
Dryland regions Livestock manure Poultry manure	6.7–11 t/ha Half of irrigation region	10 t/ha (to salt tolerant crops)
Humid regions Livestock manure Poultry manure Slurry (5 % cattle solids)	324–45 t/ha 11–22 t/ha 4 cm depth in 30 days	324–45 t/ha 11–22 t/ha 4 cm depth in 30 days

Table 24.11 Typical percentages of cations (elemental) in dry animal manures (Credit Chen et al. (2003))

Cation	Cattle				
	Dairy	Beef	Feedlot		
Calcium (Ca)	1.2	1.06	0.69		
Magnesium (Mg)	0.55	0.3	0.34		
Sodium (Na)	0.47	0.25	0.12		
Potassium (K)	2.86	1.44	0.92		
Cation	Poultry				
	Chick starter	Pullet grower	17–40 weeks	Post-molt diet	
	Calcium (Ca)	4	4	9.6	6.9
	Magnesium (Mg)	0.66	0.68	0.91	0.96
	Sodium (Na)	0.77	0.64	0.72	0.6
Potassium (K)	2.7	2.5	3.9	3.8	
Cation	Swine				
	Nursery	Grower	Finisher		
	Calcium (Ca)	1.6	4.2	2.9	
	Magnesium (Mg)	0.61	0.86	0.62	
	Sodium (Na)	0.28	0.28	0.15	
Potassium (K)	1.6	1.6	1.2		

Example 24.6 Calculate the salinity added to a field (kg/ha) if 80 metric tons/ha by dry weight of dairy manure is applied to the field.

EC is 18.8 dS/m (Table 24.11).

$$(18.8 \text{ dS/m}) (640 \text{ mg/L/dS/m}) = 11,500 \text{ mg/L} \\ = 1.15\% \text{ by weight salts.}$$

Fresh dairy manure is 12.5 % solids. Thus, the fraction of salts in dry dairy manure is

$$(0.0115 \text{ kg salts/kg manure}) / (0.125 \text{ kg solids/kg manure}) = 0.092 \text{ kg salts/kg solids}$$

An application rate of 80 metric tons/ha is the same as 80,000 kg/ha.

$$80,000 \text{ kg/ha dry weight} * 0.092 \text{ kg salts/kg solids} = 7,400 \text{ kg/ha.}$$

Irrigation of Crops with Municipal Wastewater

Wastewater cannot have excessive nutrients for some crops. In this case, wastewater should be blended with fresh water in order to prevent excessive nutrient application.

Example 24.7 Calculate the required blend of groundwater and municipal treated wastewater in order to provide the nitrogen requirement of sorghum, which is 50 kg/ha. The treated wastewater nitrogen concentration is 24 mg/L elemental N with 75 % as ammonium and 25 % as nitrate. Organic N is less than 10 % of the nitrogen load and is ignored in this calculation. The groundwater has a nitrate concentration of 3 mg/L. Previous studies have shown that ammonium in this wastewater is effectively converted to nitrate within 1–2 days after application to soils. Because the water pH is too low for ammonia formation and volatilization, the ammonia is in the ammonium ion form. Thus, it will not volatilize to the atmosphere. The depth of water application is 0.9 m/year. The crop nutrient requirement is 100 kg/ha, and 30 kg/ha of the nitrogen requirement has been applied as biosolids. Calculate the required dilution rate of the wastewater with groundwater.

The volume of water application per ha is calculated as follows:

$$(0.9 \text{ m/year})(10,000 \text{ m}^2/\text{ha}) = 9,000 \text{ m}^3/\text{ha}$$

30 kg/ha is applied as biosolids; thus, 70 kg/ha must be applied in wastewater. The required nitrogen concentration in wastewater is calculated as follows:

$$70 \text{ kg/ha} / 9,000 \text{ m}^3/\text{ha} = 0.0078 \text{ kg/m}^3 = 7.8 \text{ g/m}^3 = 8 \text{ mg/L N}$$

The NO₃ –N concentration in the wastewater is 24 mg/L, three times greater than what is required. Calculate the fraction of wastewater as follows:

$$C_T = C_{WW}F_{WW} + C_{GW}F_{GW}$$

$$8 = C_{WW}F_{WW} + C_{GW}(1 - F_{WW}) = 24 F_{WW} + 3(1 - F_{WW})$$

$$8 = 23 F_{WW} + 3 - 3 F_{WW} \rightarrow F_{WW} = 5/20 = 1/4$$

where

C_{applied} = application concentration, mg/L

C_{WW} = wastewater concentration, mg/L

F_{WW} = wastewater fraction,

C_{GW} = groundwater concentration, mg/L

F_{GW} = groundwater fraction.

The fraction of wastewater is ¼; thus, three parts ground water is required for every part wastewater.

Questions

1. Explain the meaning of Eq. 24.1 in a sentence.
2. Integrate Eq. 24.1 and derive Eq. 24.2.
3. Explain the similarity between Eqs. 24.2 and 24.3, and explain the justification for using Eq. 24.2 for calculating effluent concentration from a wetland (Eq. 24.3).
4. Show how Eq. 24.5 is derived from Eq. 24.4.
5. Explain the meaning of Eq. 24.6.
6. Repeat the area-based calculations of Example 24.1, but use 25 °C and 10 °C instead of 20 °C and 4 °C.
7. Treated wastewater has a BOD₅ of 100 mg/L, and flow rate is 200 L/min. What is the required area of a FWS wetland? Calculate based BOD load and hydraulic load. Design for an effluent BOD of 12 mg/L.
8. Why is there a minimum acceptable BOD₅ loading rate for wetlands?
9. Calculate the size of a FWS wetland required to treat an animal waste effluent stream. The desired TN concentration on the discharge side of the wetland is 30 mg/L, the waste flow rate is 50 m³/day, and the TN concentration in the dairy waste effluent is 200 mg/L.
10. A storage pond is expected to receive 10,000 m³ of manure, clean water, and wastewater during a 6 month storage period (winter) (50 m³/day * 200 days). The pond is only pumped once every 2 years and is expected to have settling of 600 m³ of solids during the 2 year interval. The normal depth of evaporation during the winter is 0.5 m, and the expected precipitation during the winter is 0.25 m. The depth of the 25-year 224-hour storm is 10 cm. The dimensions of the base of the pond are 20 × 20 m. The side slope of the pond is 2.5:1. (2.5 run × 1 rise). Calculate the depth of the pond.
11. A dairy farm has 500 lactating dairy cows in Central Arizona. Average mass/cow is 500 kg. Cows are kept in open lots, and 95 % of manure is dried (not put in ponds). The 5 % of manure from the milking parlor is washed into an anaerobic waste storage pond with 6 L water/day/cow wash water. The maximum pond operating depth is 4 m. Side slopes are 2.5:1 (2 horizontal by 1 vertical). The 25 year – 24 hour storm is 7 cm. Annual precipitation is 15 cm, and mean annual evaporation is 200 cm. Soils on the sites for waste application are well drained sandy loams and have a leaching index of 6 (6 inches (15 cm)

percolates below the root zone). The organic matter content is $< 2\%$. The soils are flood irrigated. Soil slopes are close to dead level. Crop is cotton. Required annual nitrogen addition is 150 kg/ha nitrogen (N). Assume that no extra phosphorous or potassium are required, but that there is no environmental hazard associated with overapplication of phosphorous or potassium in these soils and in this hydrologic setting with no adjacent surface water bodies. Manure is applied by truck in spring just before planting when soil is warm and dry. Assume that the storage period is 365 days and use average evaporation rate during the year. Manure has been applied for several years every spring and is incorporated into the soil by plowing within 1 day of application. Calculate application rates for truck application of dried manure and for sprinkler application of liquid manure from the waste storage pond. Assume that 150 m³/yr remain on the bottom of the pond each year.

12. Calculate the dry manure salinity application rate (kg/ha) for question 11.
13. Calculate the salinity application rate if 20 t/ha poultry manure (dry weight basis) is applied to a field.
14. Calculate the required blend of groundwater/wastewater to provide 200 kg/ha. The municipal wastewater concentration after secondary treatment is 15 mg/L N with 75 % ammonia in an arid region. The crop requires 1.2 m depth of water. Groundwater has 6 mg/L nitrate.

References

- Chen et al. (2003) Value added chemicals from animal manure. Department of Energy Pacific Northwest National Laboratory and Washington State University. www.pnl.gov/main/publications/external/technical_reports/PNNL-14495.pdf
- Fulhage, C, Pfost D (2000) Calibration of lagoon irrigating equipment. Missouri Extension. Department of Agricultural Engineering. <http://extension.missouri.edu/p/EQ327>
- Fuller WH, Warrick AW (1985) Soils in waste treatment and utilization, vol 1. CRC Press, Boca Raton
- Knight RL et al (1995) Arizona guidance manual for constructed wetlands for water quality improvement. Arizona Department of Environmental Quality, Phoenix
- Lusk P (1998) Methane recovery from animal manures. The current opportunities casebook. Prepared by Resource Development Associates for the National Renewable Energy Laboratory. <http://www.nrel.gov/docs/fy99osti/25145.pdf>
- Meisinger JJ, Randall GW (1991) Estimating nitrogen budgets for soil-crop systems. In: Managing nitrogen for groundwater quality and farm profitability, vol 5, pp 85–124
- Natural Resources Conservation Service, Agricultural Waste Management Field Handbook (AWMFH) (1996). Part 651. <http://www.nrcs.usda.gov/wps/portal/nrcs/detail/national/water/quality/?cid=stelprdb1044732>
- U.S. Environmental Protection Agency (1988) Design manual. Constructed wetlands and aquatic plant systems for municipal wastewater treatment. Office of Research and Development. Center for Environmental Research Information. <http://water.epa.gov/type/wetlands/upload/design.pdf>