University Curriculum Development for Decentralized Wastewater Treatment

Spray Dispersal

Bruce Lesikar
Vance Weynand
Mathew Lilie

December 2004

NDWRCDP Disclaimer

This work was supported by the National Decentralized Water Resources Capacity Development Project (NDWRCDP) with funding provided by the U.S. Environmental Protection Agency through a Cooperative Agreement (EPA No. CR827881-01-0) with Washington University in St. Louis. These materials have not been reviewed by the U.S. Environmental Protection Agency. These materials have been reviewed by representatives of the NDWRCDP. The contents of these materials do not necessarily reflect the views and policies of the NDWRCDP, Washington University, or the U.S. Environmental Protection Agency, nor does the mention of trade names or commercial products constitute their endorsement or recommendation for use.

CIDWT/University Disclaimer

These materials are the collective effort of individuals from academic, regulatory, and private sectors of the onsite/decentralized wastewater industry. These materials have been peer-reviewed and represent the current state of knowledge/science in this field. They were developed through a series of writing and review meetings with the goal of formulating a consensus on the materials presented. These materials do not necessarily reflect the views and policies of University of Arkansas, and/or the Consortium of Institutes for Decentralized Wastewater Treatment (CIDWT). The mention of trade names or commercial products does not constitute an endorsement or recommendation for use from these individuals or entities, nor does it constitute criticism for similar ones not mentioned.

Citation of Materials

Lesikar, B.J., V. Weynand, and M. Lilie 2005. Spray Dispersal: Operation and Maintenance Text. *in* (M.A. Gross and N.E. Deal, eds.) University Curriculum Development for Decentralized Wastewater Management. National Decentralized Water Resources Capacity Development Project. University of Arkansas, Fayetteville, AR.

Spray Dispersal

Chapter 1
Introduction

Water Reuse

Water is an important resource for maintaining our lives. Many areas in the United States are facing water demands that exceed the fresh water supplies. Wastewater is one resource available to meet part of our water demand and the supply of wastewater increases as the population grows.

Spray application systems can be used to supplement landscape irrigation. Spray application systems apply wastewater directly to the ground surface similar to any lawn sprinkler system, providing wastewater for utilization by landscape plants. Uniform application of the water distributes the reclaimed water throughout the landscape. Because application rates for on residential systems are based on evapotranspiration rates during the winter months and peak loading from facilities, the wastewater application rate should be considered supplemental rather than full watering of one's landscape. Selection of drought tolerant plants will allow more efficient utilization of the wastewater and nutrients. Supplemental watering will be needed for maintenance of relatively high water requirement plants. Municipal systems application rates, however, can be determined based on the water requirements of the plants. This approach will result in a storage requirement during periods with lower evapotranspiration rates.

Municipal and onsite spray dispersal systems have similar design requirements. However, the main difference is application rate and the subsequent requirement for storage on municipal systems. Onsite spray dispersal systems have a relatively low application rate which is code specific and do not require storage. Municipal spray dispersal systems are designed based on water requirements of the crop and an estimation of the evapotranspiration at a given location. Storage is required for municipal spray dispersal systems because you do not distribute water during periods of low evapotranspiration.

Evapotranspiration

Evapotranspiration (ET) is the combined effects of soil evaporation and transpiration of plants. Soil evaporation is the rate at which water is transformed from a liquid to a gas in the soil. Transpiration is the rate at which liquid water is absorbed by plant roots, transported through the plant and discharged into the atmosphere as water vapor.

There are several methods used to calculate the ET for a given area. These methods differ by the data requirements and level of sophistication. The most accepted method is the FAO Penman-Monteith Method (Equation 1).

The FAO Penman-Monteith method uses temperature, humidity, wind and solar radiation for weekly, ten-day or monthly calculations of ET_o for a given location

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34 u_2)} \qquad (1)$$

where:

ET_o = evapotranspiration for grass reference crop (mm/day)
R_n = net radiation at crop surface (MJ/day/m^2)
G = soil heat flux density (MJ/day/m^2)
T = mean daily air temperature at 2m height (^oC)
u_2 = wind speed at 2m height(m/s)
e_s = saturation vapor pressure (kPa)
e_a = actual vapor pressure (kPa)
e_s- e_a = saturation vapor pressure deficit(kPa)
D = slope of vapor pressure curve (kPa/^oC)
g = psychrometric constant (kPa/^oC)

See Appendix A for complete Penman-Monteith method ET calculation instructions.

Apart from the site location, the FAO Penman-Monteith equation requires air temperature, humidity, radiation, and wind speed data for daily, weekly, ten-day or monthly calculations. It is important to verify the units in which the weather data are reported.

Color Coding

Color coding is one method to differentiate reclaimed water from potable water irrigation systems. In order to identify a system that uses reclaimed water from potable water, all pipe, valve box covers, and sprinkler tops have to be permanently colored purple. Purple color coding is a universal standard for designation of reclaimed water. This color coding system and an educational program will greatly reduce the risk of cross connection with potable water supplies.

Water Quality Requirements

Residential onsite wastewater treatment systems using a spray dispersal system must have an effluent that meets secondary quality effluent standards (BOD_5 <25mg/L and TSS <25mg/L) and be disinfected before dispersal. Some states, however, require more stringent water quality standards. Municipal spray dispersal systems may have different water quality standards. These standards may allow a lesser quality of water when coupled with a method of restricting access to the spray dispersal fields. You will need to check your local regulations when evaluating the water quality requirements.

Disinfection

Effluent must be disinfected if it will be dispersed using an onsite spray dispersal system. Because of the potential risk of human contact with the wastewater, the wastewater must be properly disinfected. Some municipal spray dispersal systems have limited risk of public access and subsequently do not require chemical disinfection of the reclaimed water. For addition information on disinfection, see the disinfection module.

Spray Dispersal

Chapter 2
System Components

A series of components are designed and assembled together to construct a spray dispersal system. These components are discussed in this chapter to develop an awareness of these components.

Pumps

Each system type has its own criteria for selecting a pump. This discussion will be general and the manufacturer's design recommendations must be followed.

The pump is sized to deliver the flow and pressure required for uniform application of the wastewater. The maximum operating pressure at the distribution head for an onsite spray dispersal system is recommended to be 40 psi of less. This pressure was selected because it minimized the development of smaller droplets that are susceptible to drift.

The typical pump used for a single-family spray dispersal system is a 110 volt high head pump turbine-type pump.

Pump Tanks

Pump tanks are used in onsite wastewater treatment systems to collect and store effluent before the effluent is dosed to the final treatment area. The pump tank is a concrete, fiberglass or polyethylene container that collects wastewater. The tank contains a pump, pump controls, and a high-water alarm.

A pump tank is sized to hold: the water volume dosed during a dosing event, a minimum volume for proper operation, and storage capacity after an alarm is triggered. The water volume dosed during a dosing event is determined based on the daily flow from the facility, the type of distribution system and how often the land application area is dosed. A spray dispersal system can be dosed either when a set volume is collected ("on-demand" system) or one time during the night ("night dosing"). An "on-demand" system requires a smaller storage for a dosing event than a "night dosing" system because the "night dosing" system must store the total daily flow. For example, a three bedroom home with a 240 gallon per day flow could dose three times a day with a dosing volume of 80 gallons per dose. The "night dosing" system must store all 240 gallons of water until night.

Municipal systems will generally utilize a lined pond to store water for distribution.

These ponds will serve as the reservoir for water waiting to be distributed and will need a volume designated for storage during periods of no application. This storage requirement can approach 120 to 150 days of design flow in some areas.

Supply lines

Supply lines include all of the different lines supplying effluent to the spray heads. These different lines include manifolds, laterals and risers. Supply lines need to be designed properly to provide uniform effluent dispersal. All lines to the individual spray heads need to be the same length and size. If they are not the same length and size, the lines need to be designed to have the same friction loss in each line. The supply line can also refer to the main supply line delivering water to the manifold. In cold weather, the supply line must be properly drained to prevent freezing. Figure 2.1 illustrates different components of a spray dispersal system.

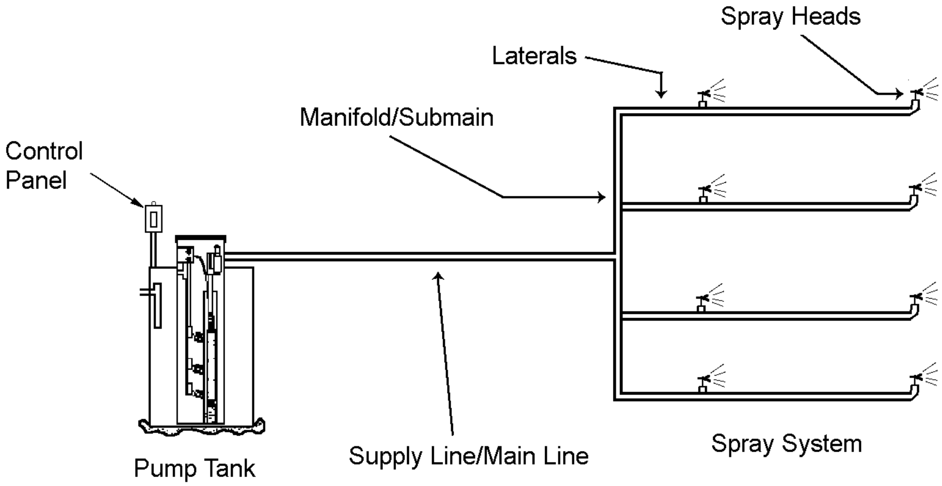


Figure 2.1: Components of a spray dispersal system.

Manifolds

A supply manifold supplies effluent to different zones of a system. Manifolds provide a centralized location for the placement of control valves to control the flow to the different zones. Manifolds are designed to carry the proper flow and pressure to all of the heads in the system or zone.

Laterals

From the manifold, laterals supply water to the individual spray heads. Typically, laterals are the largest portion of the supply lines.

Risers

Risers are used between the lateral and the spray head to protect the lateral from damage and convey the water to the appropriate location. Two approaches are used when incorporating risers into a spray dispersal system: 1) at-grade installation of spray heads, and 2) above-grade installation of spray heads.

At-grade risers should be flexible to allow downward movement when the spray heads are accidentally hit or run over by lawn care equipment or other objects. There are three different types of risers used in the landscape irrigation industry. The first type, a swing joint, is a combination of nipples and elbows that provides movement at each joint. The second option is to use a section of flexible pipe at each joint to allow movement. The final type, a flexible nipple, is a piece of ridged but flexible plastic pipe connecting the lateral and the spray head. Flexible nipples come in a variety of lengths for proper head placement. Figure 2.2 illustrates the different riser configurations.

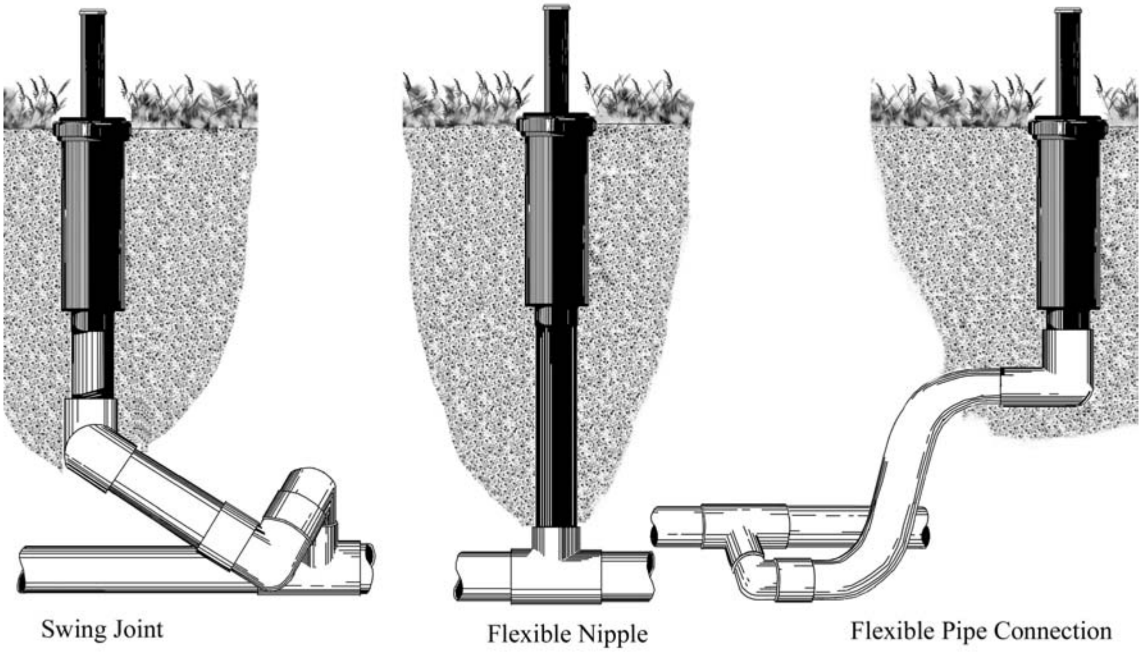


Figure 2.2: Different Riser Types (Choate, 1994).

Above-grade risers extend the spray head above the ground surface. These risers are rigid and support the spray head. The risers may be used to get the spray head above the crop utilizing the water. These risers assist in ensuring vegetation is not blocking the distribution pattern of the spray head. Elevated risers are subject to freezing and this risk should be considered in the design.

Air Relief

Air relief in a system is necessary to remove air that enters the supply lines. Air relief prevents siphoning of the pump tank when the spray heads are located down gradient of the pump tank. Air relief allows certain types of spray heads to retract after each cycle.

Heads

The spray heads are the final component in a spray dispersal system. Heads are sized by their flow rate and distance of throw at different operating pressures. When selecting a spray head, one can choose from several different types of heads including: impact, rotary, and spray heads. It is recommended to use spray heads with low angle nozzles (15 degrees or less trajectory) for onsite spray dispersal systems. Spray head tops must be colored purple to identify the system as distributing reclaimed water.

Flow Rate

The flow rate of a head is a function of the operating pressure and nozzle size. The flow rate of a head must be designed with the infiltration rate of the soil to eliminate runoff and deep percolation.

Distance of Throw

The distance of throw or radius of throw is also a function of operating pressure and nozzle size (shown in Figure 2.3). When deciding the distance of throw of a head, one must consider the total dispersal area requirements and separation distances.

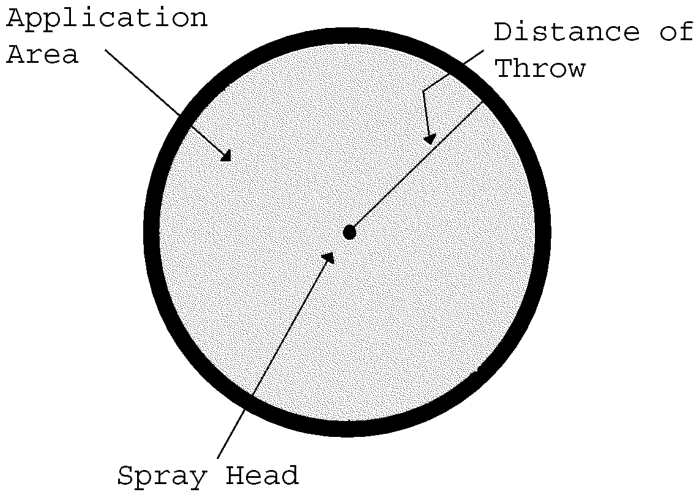


Figure 2.3: Distance of throw and application area for a single spray head.

Head Types

There are three different types of heads used in dispersal of effluent.

- ***Impact:*** Impact drive heads use a weighted, spring-loaded drive arm to rotate the head. The effluent stream deflects the arm sideways while the spring pulls the arm back to the nozzle. The impact against the nozzle causes the head to rotate. Impact heads can operate at a full 360 degrees or partial circles.

- ***Rotary:*** Rotary drive heads use either a gear drive system or a ball drive system. Rotary heads can travel through different ranges of motion ranging from 20 to 360 degrees depending on the manufacturer. Effluent entering the base of a gear drive head passes through a stator that converts it into high pressure jets. These jets hit a turbine impeller that turns a gear system which turns the nozzle of the head. Inside a ball drive rotary head, a free metal ball spins within the body of the head caused by an angle in the orifice plate. As the ball spins, it hits a drive arm that rotates the nozzle. Rotary heads are normally of a pop-up variety that extend from the head's body during use and retract after use.

- ***Spray:*** Spray heads provide uniform application of water in a variety of spray patterns to fit any application area. Different patterns include a spray pattern from 90^o to 360^o, end strip, side strip, center strip, and high low (Figure 2.4). Spray heads are normally a pop-up variety as well.

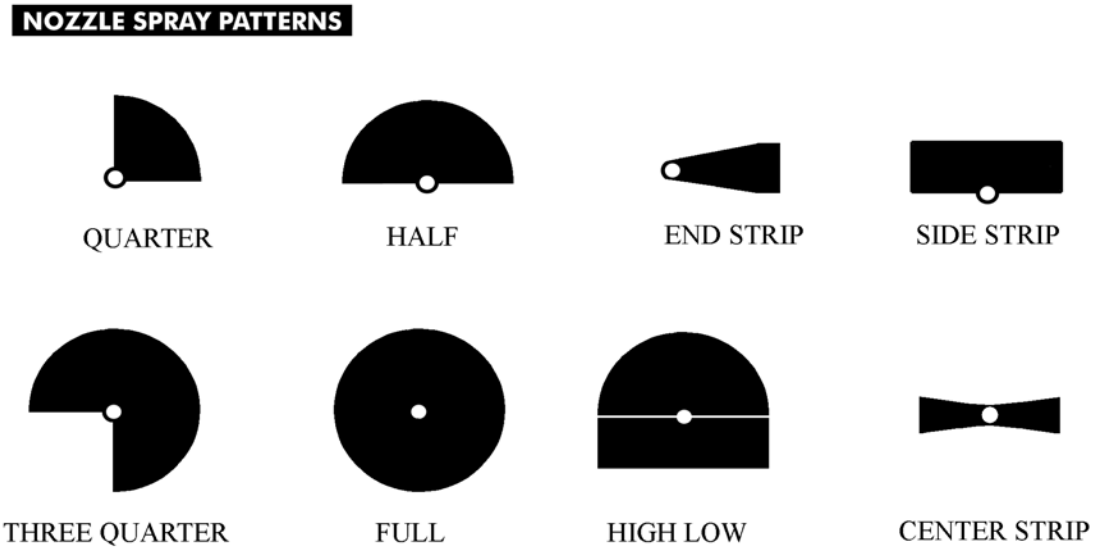


Figure 2.4: Different spray patterns available (K-Rain, 1999).

Disinfection

Treated effluent must be disinfected before being dispersed with onsite surface application. The degree of disinfection depends on accessibility to the system. Systems with open public access require greater attention to disinfection than those that have restricted accessibility. Disinfection methods available for proper disinfection include: chlorination, ozonation, and ultraviolet radiation. Please refer to the Disinfection module for greater discussion on disinfection.

Controls

Spray dispersal systems can be either controlled by an "on-demand" sensor or a commercial electronic controller depending on the location of the application area and the separation distance to the property line. Systems can be "night dosed" to minimize the potential for human contact when separation distances are limited.

"On-demand" dosing uses the pump floats in the pump tank to control the dosing of the effluent. The system is dosed when a set volume is collected in the pump tank. The effluent is then dosed to the dispersal area.

When a “night dosed” system is used, the effluent is dispersed once a day between midnight and 5 a.m. The use of commercial timers is not limited to situations where separation distances cannot be met. A homeowner may choose to have the effluent dispersed at night if given the option.

Spray Dispersal

Chapter 3
Design Considerations

Site and Soil Considerations

The wastewater treatment system should be worked into the landscape to take advantage of natural vegetation, topography, and soils. The topography of the site refers to the slope of the land and the natural drainage channels that are formed by this slope. Rainfall runoff should be diverted from the treatment system and final treatment and dispersal area to prevent saturation of the soil and possible system failure. The soils should be evaluated on the site to select the best location for the system. Soil types can be fairly uniform in a yard or can change drastically in just a few feet. It is important to place the land application area in a well-drained soil.

The final treatment and dispersal area needs to be evaluated to determine the most restrictive layer in the soil profile. The most restrictive layer will determine the quantity of water that can be applied to the soil, since it limits the flow of water through the soil. The ability of each layer to transport water is carefully considered, and then the lowest transport rate is used to determine the wastewater loading rate to the soil. The wastewater loading rate and the quantity of water generated in the home are used to determine the size of the application area.

Soil Survey/Maps

The United States Natural Resources Conservation Service has surveyed and mapped the soils in counties across the United States. The use of the county soil surveys with their maps is another source of information on the characteristics and properties of soils in an area. These surveys should not be used alone, but in conjunction with a site's soil evaluation.

Infiltration Aspects

The most important characteristic of soils with respect to their infiltration capacity is their particle-size distribution, which is a measure of the relative fineness or coarseness of the particles in the soil. You probably already know that a clay soil (very fine particles) is a much better filter than a sandy soil (coarse particles). The particle size of a soil governs the porosity (total amount of pore space in a soil) and the permeability (how fast water can move through a soil). You might think that a sandy soil is much more porous than a clayey soil, but clayey soils actually have a much *higher* porosity than sandy soils. The important factor is the size of the actual pores. In a clayey soil, most of the pore space is very fine and usually very convoluted, so that water flows very slowly in these soils.

Site Preparation

Preparation of the site can minimize potential problems in the future. Detail to the layout of the system and the drainage of the site assist in the location of the system components.

Site Leveling and Drainage

Site preparations include leveling the site for the installation of the different components. The dispersal area should have a uniform slope not exceeding 15 percent unless the site is landscaped and terraced to minimize runoff. Adequate drainage of the site is needed to promote runoff from rainfall from the dispersal area as well as to prevent water to runon to the dispersal area.

Surface Water Runoff

In preparing the dispersal area, drainage of excess rainfall is necessary to prevent the soil from being hydraulically overloaded.

Surface Water Runon

Water that would normally runon to the dispersal area should diverted away form the dispersal area to prevent the soil from being hydraulically overloaded. In times of wet weather, the ET of the dispersal area is at its lowest. Any additional water puts the system under stress, creating a potential for the effluent to runoff of the dispersal area and contaminate surface or groundwater.

Irrigation Verses Dispersal

A common misconception for spray application systems for onsite systems is that the effluent will fulfill the water requirements of the cover grass in the dispersal area. Large municipalities, however, can disperse the effluent based on evapotranspiration. This is possible because of the continuous monitoring of the entire system and the storage of effluent during time of low ET.

Effluent Application Rates

The application rate of an onsite spray system is determined based on the month in which the ET is the lowest. Spray application systems are designed such that all of the effluent is utilized by the cover grass. In a properly designed spray application system, there should be no deep percolation of effluent into the soil or runoff from the dispersal area. Municipal systems require that the application rate to be calculated on a monthly basis.

Daily Loading

The allowed daily loading rates of effluent for surface application for onsite systems is based on the ET rate of month in which the ET is the lowest. Municipalities apply effluent based on the daily ET rate of the cover crop.

Plant Water Requirements

Plant water requirements are calculated by the FAO Penman-Monteith method described at the beginning. For onsite treatment systems, additional water will need to be applied to the dispersal area to maintain a plush cover grass during the summer months due to the low application rate calculated for winter months. In municipal systems, the full plant requirement may be applied as long as the nitrogen loading rate does not exceed 120 percent of the nitrogen requirement of the cover crop.

Infiltration Rates of Soils

Soil infiltration rates are based on the Soil Classification System and soil structure.

Nutrient Loading

Nutrient loading refers to the amount of nutrients in the effluent applied to the dispersal area. Currently there are no regulations for onsite facilities for nutrient loading. For municipalities, current regulations have limits on nitrogen.

Water Storage Requirements

Water is stored in a pump tank prior to dispersal for onsite systems. A pump tank's storage is divided into an alarm volume, a dosing volume, and a minimum operation volume. The alarm volume is the volume above the normal dosing volume that triggers an alarm indicating a problem with the system. The dosing volume may be several different volumes. If night dosing is required, the dosing volume is the total daily flow of the system. Other systems have predetermined volumes set by the infiltration rate of the soil or total application rate. Systems can be either controlled by commercial timers at certain times of the day or "on-demand" in which the pump is controlled by the floats in the pump tank. On-demand systems dose effluent whenever a predetermined amount of effluent enters the pump tank. This particular style of controlling the dosing of effluent is usually the lowest cost, but caution needs to be taken when laying out the system. There is a potential for the system to dose during the day when someone is in the dispersal area. This could be children or guests during a party at the house. The minimum operating volume is the volume of water from the bottom of the tank to the inlet of the pump.

Municipal systems require a much larger storage volume for the effluent. A municipal system requires the storage of effluent during times of low ET for the cover crop. Typically this storage is between two and four months.

Water Distribution

Effluent is distributed below the ground surface to the spray heads. No hose bibs can be connected to the distribution line. A non-threaded sampling port is required within the pump tank for monitoring.

The size of the dispersal area determines the number of spray heads necessary to disperse the effluent. The number of heads and their flow rate and the pump size selected may require the use of different zones. Dividing the dispersal area in-to different zones allows the pump to operate within the recommended range of pressure and flow rate.

Uniformity

Uniform application of effluent reduces the risks of human contact and contamination of groundwater and surface water. When effluent is evenly dispersed within the application area, the system has the opportunity to function properly. When one portion of the application area is overloaded, the water may runoff or percolate into the groundwater. When selecting the spray heads for a system, the application uniformity should be checked to ensure uniform application within the design constraints.

Application Rate

To reduce the risk of runoff and deep percolation, the application rate of effluent needs to be based on the lowest ET and lowest rate that the soil can accept before runoff that does not induce deep percolation for onsite systems. Application rates for municipal systems account for the ET requirement of the cover crop, deep percolation (to avoid saline build up in the soil), and application efficiency. In order not to exceed the infiltration rate, the effluent in onsite systems may need to be applied several times a day rather than once a day, or additional dispersal area may be required for system with large flows and "night dosing".

The application rate of wastewater can be done on a hydraulic loading rate, based on soil permeability or a hydraulic rate based on nutrient limits, typically nitrogen. The hydraulic loading rate is the volume of wastewater applied per unit area of land over at least one loading cycle. Hydraulic loading rate is commonly expressed in cm/week or m/yr (in/week or ft/yr) and is used to compute the land area required for the spray dispersal systems. The hydraulic loading rate used for design is based on the more restrictive of two limiting conditions. A separate case is considered for those systems in arid regions where crop revenue is important and the wastewater is used as a valuable source of irrigation water. For such systems, the design hydraulic loading rate is usually based on the irrigation requirements of the crop. To calculate the hydraulic loading rate based on soil permeability, the EPA water balance method is used (Equation 2).

$$L_W = ET - Pr + P_W \quad (2)$$

where: L_W = wastewater hydraulic loading rate
ET = evapotranspiration rate
Pr = precipitation rate (5 year return cycle add 12-15 %)
P_W = percolation rate (permeability (in/hr or cm/hr) X 24 hr/day X (design factor: 4-10%))

The following steps should be taken to calculate the hydraulic loading rate based on soil permeability.

1. Determine the design precipitation for each month based on a 5-year return period frequency analysis for monthly precipitation. Alternatively, use a 10-year return period for annual precipitation and distribute it monthly based on the ratio of average monthly to average annual precipitation.

2. Estimate the monthly ET rate of the selected crop.

3. Determine by field test the minimum clear water permeability of the soil profile. The minimum soil permeability is based on areas of different soil types.

4. Establish a maximum daily design percolation rate that does not exceed 4 to 10% of minimum soil permeability. Percentages on the lower end of the scale are recommended for variable or poorly defined soil conditions. The percentage to use is a judgment decision to be made by the designer. The daily percolation rate is determined as follows:

$$P_W\,(\text{daily}) = \text{permeability, cm/hr}(34\,\text{h/d})(4\ \text{to}\ 10\%)$$

5. Calculate the monthly percolation rate with adjustments for those months having periods of nonoperation. Nonoperation may be due to:

    a. Crop management. Downtime must be allowed for harvesting, planting, and cultivation as applicable.
    b. Precipitation. Downtime for precipitation is already factored into the water balance computation. No adjustments are necessary.
    c. Freezing temperatures. Subfreezing temperatures cause soil frost that reduces surface infiltration rate. Operation is usually stopped when this occurs. The most conservative approach to adjusting the monthly percolation rate for freezing conditions is to allow no operation for days during the month when the mean temperature is less than 0 °(32 °F). Nonoperating days due to freezing conditions may also be estimated using the EPA-1 computer program without precipitation constraints. For forest crops, operation can often continue during subfreezing conditions.
    d. Seasonal crops. When single annual crops are grown, wastewater is not normally applied during the winter season, although applications may occur after harvest and before the next planting. The design monthly percolation rate may be calculated as follows:

$$P_W\,(\text{monthly}) = [\text{Pw (daily)}]\ \text{x (No. of operating d/mo)}$$

6. Calculate the monthly hydraulic loading rate using Equation 2. The monthly hydraulic loadings are summed to yield the allowable annual hydraulic loading rate based on soil permeability [$L_{W\,(p)}$]. Downtime is allowed for freezing conditions, but pasture management does not require harvesting downtime.

The allowable hydraulic loading rate based on soil permeability calculated by the above procedure $L_{W\,(p)}$ is the maximum rate for a particular site and operating conditions, and this rate will be used for design if there are no other constraints or limitations. If other limitations exist, such as percolated nitrogen concentration, it is necessary to calculate the allowable hydraulic loading rate based on these limitations and compare that rate with the $L_{W\,(p)}$. The lower of the two rates is used for design. Procedures for calculating hydraulic loading rate based on soil permeability were obtained from North Carolina State University Soil and Water Environmental Technology Center.

Example

Find the hydraulic loading rate based on soil permeability for a site that receives 50 inches of rain annually, with an annual ET of 35 inches and soil permeability of 0.0066 in/hr.

$$L_W = ET - Pr + P_W$$

ET = 35 in/year
Pr =50 in/year + 12% for a five year return period = 56 in/year
Pw =0.005 in/hr = 0.12 in/day = 43.8 in/year

$$L_w = 35 - 56 + 43.8$$
$$L_w = 22.8 \text{in/year}$$
$$L_w = 0.062 \text{ in/day}$$
$$L_w = 0.038 \text{ gal/ft}^2$$

Hydraulic loading rates based on nutrient requirements of the cover crop are typically lower than the application rate based on ET or soil permeability. Typically the hydraulic loading rate based on nutrient loading is based on nitrogen requirements of the cover crop, but with recent developments of the Total Maximum Daily Load requirements, some impaired watersheds are required to apply effluent based on the phosphorus requirements of the cover crop.

When applying on a nitrogen base, total nitrogen is used to calculate the hydraulic application rate of the effluent. During application, a percentage of the nitrogen is lost to volatilization. When using sprinkler irrigation, volatilization can range from 15 to 40 percent. Additionally only 50% of the nitrogen is available to the plant in the first year. Organic nitrogen releases slowly to plants over several years. After a few years of regular application, the available amounts of nitrogen are equal to the yearly application rate (MWPS, 1993). All of the phosphorus and potassium applied annually is plant available.

Spray Head Elevation

There are two options when setting the elevation of the spray head. Fixed impact sprinklers have the head fixed above the ground surface. Pop-up heads are placed below the ground surface. In both cases, the height of the head or the pop-up must be higher than the grass to ensure uniform application. Heads that are placed above the ground surface need to be marked to prevent accidental damage by lawn equipment.

Matching Distribution Method to Vegetation Management

The type of distribution system used depends on the amount of management the dispersal area will be receiving. For example, if the dispersal area will be part of the main lawn, one would probably prefer to have pop-up spray heads that are not visible at all times, or if the dispersal area is towards the back of the property and not visible from the house, the homeowner would be more likely to have fixed spray heads above ground.

Pump Selection

A pump is selected for a system by determining the total flow and head of the system. After finding these two values, the pump can be selected from manufactures' pump curves. An alternative method of pump selection is to select a pump and design the system to match the flow and head of the pump. Most residential systems are designed around a particular pump rather than designing a system and then selecting the pump. This is the preferred process because of the limited number of reasonably priced pumps available for use in the residential marketplace.

Total Flow

The total flow of the distribution system is found once the spray head is selected. Spray heads are sized by their flow rate and radius of distribution at a certain pressure. The pressure of a spray application system is limited to 40 pounds per square inch.

Total Dynamic Head

The total dynamic head of a system is divided into friction loss and head required for the desired pressure.

Friction Loss

The friction loss in a pipe system can be found by using the Hazen-Williams friction loss (Equation 3).

$$h_f = 10.46L\frac{\left(\frac{Q}{C}\right)^{1.852}}{D^{4.871}} \qquad (3)$$

where:

h_f = friction head loss in feet
10.46 = constant used to convert units
L = pipe length in feet
Q = flow rate in gallons per minute (gpm)
D = inside diameter of pipe in inches
C = Hazen-Williams friction factor for given pipe material.

The Hazen-Williams friction factor has been calculated for a number of different types pipe materials. Table 3.2 gives the friction factor for several different materials used in spray dispersal systems. When designing a system, velocity within pipes should be less than five feet per second to reduce water hammer.

Table 3.1: Suggested values of Hazen-Williams friction factor (C).

Pipe Type	**Values of Hazen-Williams friction factor (C)**		
	Range	**New Pipe**	**Design**
Polyvinyl Chloride (PVC)	145-160	150	150
Polyethylene (PE)	130-150	140	140
Asbestos-Cement	140-160	150	140
Cement-Lined Steel	140-160	150	140

Example

Example problem using the Hazen-William friction loss equation. Find the friction loss for 250 feet of 1 ½ in PVC pipe with a flow rate of 27 gallons per minute using the Hazen Williams friction loss equation.

$$h_f = 10.46\,L\frac{\left(\frac{Q}{C}\right)^{1.852}}{D^{4.871}}$$

h_f = friction head loss in feet
10.46 = constant used to convert units
L = pipe length in feet
Q = flow rate in gallons per minute (gpm)
D = inside diameter of pipe in inches
C = Hazen-Williams friction factor for given pipe material
C = 150 for PVC pipe

$$h_f = 10.46(250\,ft)\frac{\left(\frac{27}{150}\right)^{1.852}}{1.59^{4.871}}$$

h_f = 11.40 feet

Pressure Head

The pressure head of a system is the required energy of the pump to produce the final pressure at the spray head. One pound per square inch correlates to 2.31 feet of head. For an operating pressure of 30 pounds per square inch, one would need and additional 69.3 feet of head.

Drift Minimization

Several different steps have been taken to minimize the drifting of effluent from the dispersal area. The first is having a maximum inlet pressure for sprinklers of 40 pounds per square inch. As pressure increases, the diameter of water droplets decrease, increasing the likelihood of drift. The second is the use of low angle nozzles. Nozzles used in spray dispersal systems need a trajectory of 15 degrees or less. Trees that shelter the site also minimize drift from the site.

Setback Distances

Minimum setback distances have been established to protect public health and the environment. These distances have been established for a variety of structures and landscape features and the components of an onsite system. Please check your local regulations for specific setback distances.

Spray Dispersal

Chapter 4
System Design

Onsite Wastewater Treatment Systems

The design of a spray dispersal system for an onsite wastewater treatment system can be determined by using the following steps.

1. Determine surface area required based on facility flow and geographic location.

The critical design component of an onsite system is the total land area and the available area due to site constants and open area verses using irregular shaped areas required for application of effluent. Once the land area is determined then other components of the system can be determined.

The land area required for an onsite wastewater treatment system is determined by the application rate for the geographic area of the site and facility flow. As mentioned before the application rate is determined based month with the lowest ET rate. Look for local guidance on the application rates in your area. To determine the land area required the following equation can be used.

$$\text{Area} = Q / R_i$$

where:

Area = the land area required
Q = the flow of the facility
R_i = the application rate for the given site location

2. Determine based on site evaluation the location of the dispersal area.

The location of the dispersal area at a site is based on the land available for the application area as it relates, to the different setback distance set by local and state regulations, open areas verses using irregular shapes, topography of the site, and land use.

3. Select the type of heads, distribution pattern, and head configuration required to cover the distribution area.

Based on the layout of the distribution system the type of heads that will be used can be selected. Head types include impact, rotary, and spray; each head type can be used in variety of different configurations.

4. Based on the required application area, head type, and limits on radius, select the nozzle and operating pressure at the head. Evaluate the nozzle type and operating pressure with respect to local regulations.

   Each of the different types of heads can be configured with different nozzles and operating pressures to achieve the desired radius. Depending on local regulations the type of nozzle and operating pressure may be restricted. Nozzles with large angles of trajectory are restricted in some areas to reduce the amount of effluent that drifts. Restrictions on the maximum operating pressure

5. Determine the flow rate for the system based on the type and number of heads.

   Once the type of head, nozzle and operating pressure is determined then the flow rate of the system can be determined. Each manufacture of spray head has developed flow rate tables for different heads and nozzles at different operation pressures.

6. Determine pipe network (supply line, manifold, laterals, risers) required to deliver the water to the heads.

   To size the pipe network of the system first start with the supply line since it supplies water to the whole system. Then design the manifolds and laterals. When designing the size of the pipe the critical component of the design is the velocity of the water. The design velocity of the water should not exceed 5 feet per second to reduce water hammer. Additionally, try not to have too many different sizes of pipes.

7. Determine the Total Dynamic Head (TDH) for the system and the system operating curve.

   The TDH can be calculated by taking the sum of the elevation head, friction loss, and pressure head.

8. Select a pump based on the system operating curve. Because of the limited range of pumps available, the system may need to be divided into zones to have a flow and operating pressure that matches the pump.

   The different manufacturers of pumps provide a pump curve for the different pumps available. A pump curve illustrates the operating points of the pump at different flow rates and TDH. An example of a pump curve is show in Figure 4.1. Because of the limited number of pumps available, larger systems may need to be divided into zones in order to reduce the flow rate and TDH to fit into one of the available pumps.

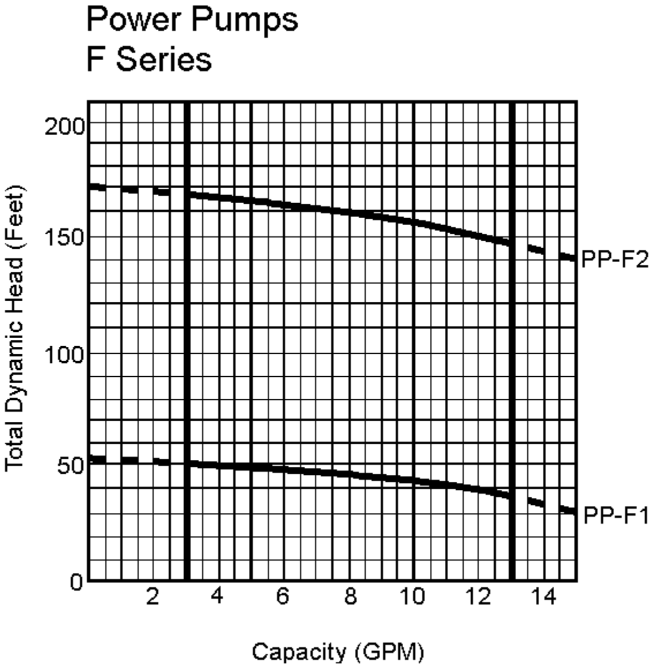


Figure 4.1: Pump Curve for Power Pumps - F Series
Note: This pump curve was created using fictitious data. Any correlation to a specific model is unintentional.

9. Evaluate application rates based on operating curve, runtime, and heads selected.

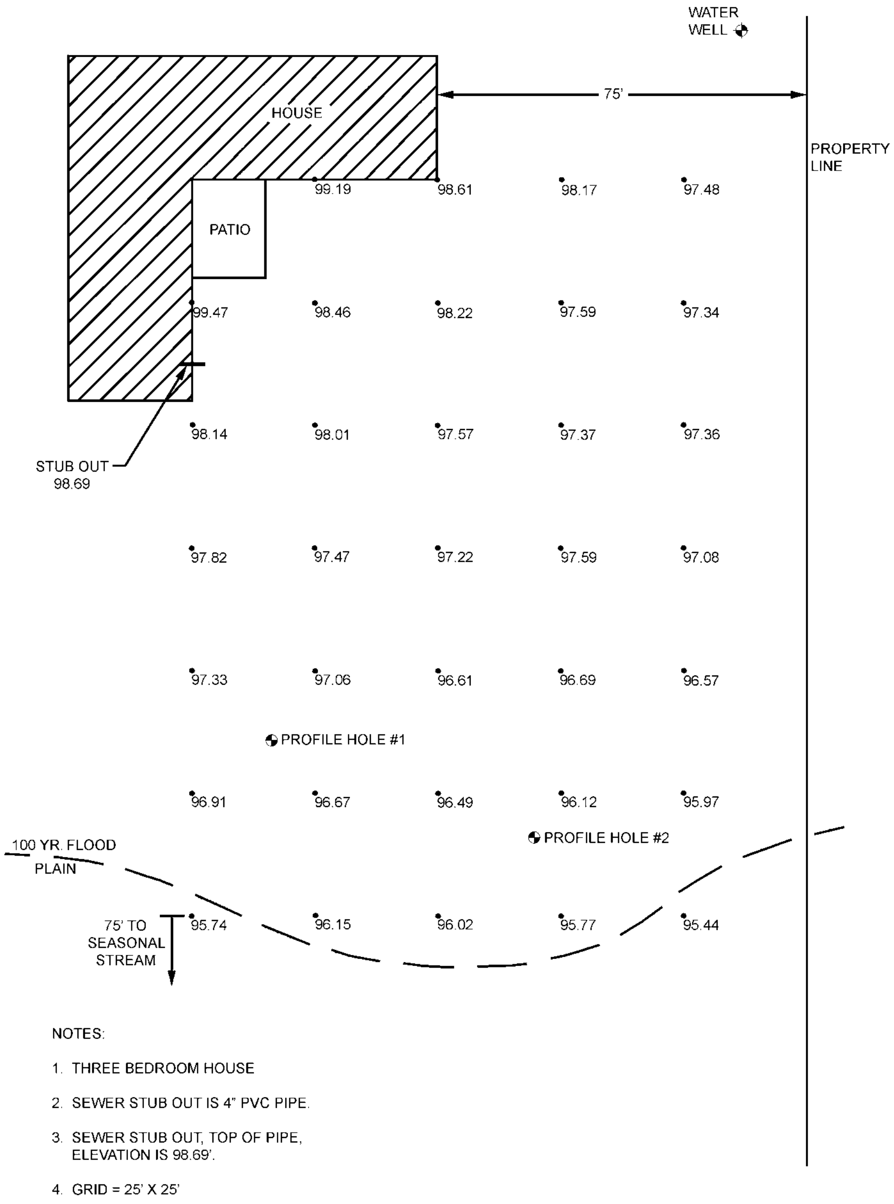
   Once all of the different components of the system are selected an evaluation of the application rates is needed to determine if the application rate of the system is uniform and within the design constants of the site. Once a system is installed, the operating point of the system will determine the actual output of the spray heads.

10. Determine the pump tank size based on pump, flow, and design constraints.

    A pump tank is sized to hold: the water volume dosed during a dosing event, a minimum volume for proper operation, and storage capacity after an alarm is triggered. The water volume dosed during a dosing event is determined based on the daily flow from the facility, the type of distribution system and how often the land application area is dosed. A spray dispersal system can be dosed either when a set volume is collected (“on-demand” system) or one time during the night (“night dosing”). An “on-demand” system requires a smaller storage for a dosing event than a “night dosing” system because the “night dosing” system must store the total daily flow. For example, a three bedroom home with a 240 gallon per day flow could dose three times a day with a dosing volume of 80 gallons per dose. The "night dosing" system must store all 240 gallons of water until night.

Example

Design a spray dispersal system for a single family residence in Hometown, U.S.A. servicing a three bedroom home with 2,300 ft^2. Treatment of the effluent will be accomplished by a Class I aerobic treatment unit.



NOTES:

1. THREE BEDROOM HOUSE
2. SEWER STUB OUT IS 4" PVC PIPE.
3. SEWER STUB OUT, TOP OF PIPE, ELEVATION IS 98.69'.
4. GRID = 25' X 25'

Figure 4.1: Example design problem for Hometown, U.S.A.

1. Determine surface area required based on facility flow and geographic location.

- Flow from facility: 3 bedroom, 2,300 ft^2
- Flow equals 240 gal./day.
- Ri for Hometown, U.S.A = 0.064 gal./ft^2/day
- Area = 240 / 0.064 = 3,750 ft^2

2. Determine based on site evaluation the location of the dispersal area.

   For the same example from step 1 the site of the proposed site is as shown in Figure 4.1. The site is an open site that slopes from the top of the site toward the seasonal stream. Soil profile indicates a class IV soil. Notice the property line and the private water well.

   Typically, a spray dispersal system is set in an area that receives the least human contact. For this site, the spray dispersal system will be placed in the lower right portion of the site. The homeowner indicated that they would like have the effluent dosed at night with a commercial timer. This allows the separation distance to the property line to be reduced depending on local regulations. Other separation distances that need to be considered are the distances from the house, water well, seasonal stream, and flood plain indicated by local regulations. For this example, the separation distances for the edge of the spray dispersal area used are shown in Table 4.1.

Table 4.1. Separation distances from edge of spray area for Hometown, USA.

From	To Surface Application (edge of Spray Area)
Private Water Well	50 ft
Streams, Ponds, Lakes, Rivers, Creeks (Measured from Normal pool elevation and water level); salt water bodies (high tide only)	50 ft
Foundations, Buildings, Surface Improvements, Property Lines, Easements, Swimming pools, and other structures	No separation distance except: Property Line 20 ft (can be reduced to 10ft if controlled by commercial timer operated between midnight and 5:00 a.m.) Swimming pools 25 ft

   Even though the separation distance can be reduced to the property line because the homeowner wants to use “night dosing”, for this example we are going to stay away from the property line more than the 20 ft setback for dosing without “night dosing”. Just because it is allowed to be closer to the property line the site allows for ample application area without getting close to the property line.

3. Select the type of heads, distribution pattern, and head configuration required to cover the distribution area.

Because the site is open, one could use a variety of impact or rotary spray heads that cover large areas with a single spray head. For this example, impact sprinkler heads will be used.

4. Based on the required application area, head type, and limits on radius, select the nozzle and operating pressure at the head. Evaluate the nozzle type and operating pressure with respect to local regulations.

   The nozzle used in this example can be selected from a table such as Table 4.2. Each nozzle can be operated at several different pressures to achieve different application areas. It is a good idea to select several different options to achieve the required application area to ensure application uniformity.

Table 4.2: Design specifications for Superior Flow spray heads.

Low Angle Nozzle	Pressure (psi)	Radius (ft)	Flow (gpm)	Spray Head Area (ft^2)	Precipitation Rate (in/hr)
SF - 1	25	23	1.3	1662	0.65
	35	25	1.8	1964	0.72
SF - 2	25	24	3.6	1810	0.96
	35	28	4.1	2463	0.89

Note: This table contains fictitious data. Any correlation to a specific model is unintentional.

Selection of Spray Heads, Option 1

- 3,750 ft^2required
- Select 2 spray heads
  One SF - 1 spray head at 35 psi, 25 ft radius, 1964 ft^2.
  One SF - 2 spray head at 35 psi, 30 ft radius, 2463 ft^2.
- Total Area = 4,427 ft^2.

Selection of Spray Heads, Option 2

- 3,750 ft^2 required
- Select 3 spray heads
  Two SF – 1 spray heads at 35 psi, 25 ft radius, 1964 ft^2 total, each area – 982 ft^2, operated on a half-circle basis
  One SF – 2 spray head at 35 psi, 28 ft radius, 2463 ft^2.
- Total Area = 4,427 ft^2.

5. Determine the flow rate for the system based on the type and number of heads.

   For the given options the flow rates of the spray are

   - SF – 1 at 35 psi = 1.8 gpm
   - SF – 2 at 35 psi = 4.1 gpm

- Total flow Option 1 = 5.9 gpm
- Total flow Option 2 = 7.7 gpm

6. Determine pipe network (supply line, manifold, laterals, risers) required to deliver the water to the heads.

   The fist step in determining the correct pipe size is to find the velocity in the pipe so that it does not exceed 5 ft/s. To determine the velocity in the pipe use the following equation.

   $Q = V*A$

   where:

   Q = Flow rate cubic feet per second (ft^3/s)
   V = Velocity feet per second (fps)
   A = Area square feet (ft^2)

   Option 1: 1/2 in SCH 40 PVC
   $Q = 5.9$ gpm $= 0.79\ ft^3/min = 0.013\ ft^3/s$
   $A = ((0.608\ in / 12)^2 * (3.14))/4 = 0.0020\ ft^2$
   $V = .013\ ft^3/s)/ .0020\ ft^2 = 6.5\ ft/s$ (exceeds 5 ft/s)

   3/4 in SCH 40 PVC
   $Q = 5.9$ gpm $= 0.79\ ft^3/min = 0.013\ ft^3/s$
   $A = ((0.810\ in / 12)^2 * (3.14))/4 = 0.0036\ ft^2$
   $V = .013\ ft^3/s)/ .0036\ ft^2 = 3.61\ ft/s$

   Option 2: 1/2 in SCH 40 PVC
   $Q = 7.7$ gpm $= 1.03\ ft^3/min = 0.017\ ft^3/s$
   $A = ((0.608\ in / 12)^2 * (3.14))/4 = 0.0020\ ft^2$
   $V = .017\ ft^3/s)/ .0020\ ft^2 = 8.5\ ft/s$ (exceeds 5 ft/s)

   3/4 in SCH 40 PVC
   $Q = 7.7$ gpm $= 1.03\ ft^3/min = 0.017\ ft^3/s$
   $A = ((0.810\ in / 12)^2 * (3.14))/4 = 0.0036\ ft^2$
   $V = .017\ ft^3/s)/ .0036\ ft^2 = 4.72\ ft/s$ (close to exceeding 5 ft/s)

   1 in SCH 40 PVC
   $Q = 7.7$ gpm $= 1.03\ ft^3/min = 0.017\ ft^3/s$
   $A = ((1.033\ in / 12)^2 * (3.14))/4 = 0.0058\ ft^2$
   $V = .017\ ft^3/s)/ .0058\ ft^2 = 2.93\ ft/s$

   Table 4.3: Specifications for SCH 40 PVC

Nominal Pipe Size (in)	O.D.	Average I.D.	Min. Wall	Nominal Wt./Ft.	Max. W.P. PSI**
1/8	.405	.261	.068	.045	810
1/4	.540	.354	.088	.081	780
3/8	.675	.483	.091	.109	620
1/2	.840	.608	.109	.161	600
3/4	1.050	.810	.113	.214	480
1	1.315	1.033	.133	.315	450
1-1/4	1.660	1.364	.140	.426	370
1 -1/2	1.900	1.592	.145	.509	330
2	2.375	2.049	.154	.682	280
2-1/2	2.875	2.445	.203	1.076	300
3	3.500	3.042	.216	1.409	260
3-1/2	4.000	3.520	.226	1.697	240
4	4.500	3.998	.237	2.006	220
5	5.563	5.017	.258	2.726	190
6	6.625	6.031	.280	3.535	180
8	8.625	7.943	.322	5.305	160
10	10.750	9.976	.365	7.532	140
12	12.750	11.890	.406	9.949	130
14	14.000	13.072	.437	11.810	130
16	16.000	14.940	.500	15.416	130
18	18.000	16.809	.562	20.112	130
20	20.000	18.743	.593	23.624	120
24	24.000	22.544	.687	32.873	120

So if Option 1 is used, 3/4 inch pipe can be used for the supply and manifolds, and if Option 2 is used, then 1 inch line needs to be used.

7. Determine the Total Dynamic Head (TDH) for the system and the system operating curve.

Total Dynamic Head calculations, Option 1:
Given
Flow rate = 5.9 gpm at 35 psi
Using 3/4 inch SCH 40 PVC pipe.

Elevation head worst case scenario with the pump placed 6 feet below the ground surface in the pump tank.

Pressure head h_p= 2.31 ft per psi = 35*2.31 = 80.85 ft

Friction loss

Friction loss of the supply line

$h_f = 10.46 * 100 * (((5.9/150)^{1.852})/(0.810)^{4.871}) = 7.29$ ft

Friction loss of the longest lateral

$h_f = 10.46 * 30 * (((4.1/150)^{1.852})/(0.810)^{4.871}) = 1.11$ ft

Friction loss through fittings of the longest lateral (1 tee, 1 elbow)

Equivalent length of straight run pipe for 1 tee = 4.9 ft
Equivalent length of straight run pipe for 1 elbow = 2 ft
Total length = 6.9 ft

$h_f = 10.46 * 6.9 * (((4.1/150)^{1.852})/(0.810)^{4.871}) = 0.26$ ft

Friction loss = 7.29 ft + 1.11 ft + 0.26 ft = 8.66 ft

TDH = Elevation head + Pressure head + Friction loss

TDH = 6 ft + 80.85 ft + 8.66 ft = 95.51 ft, Say 96 ft

Total Dynamic Head calculations, Option 2:
Given
Flow rate = 7.7 gpm at 35 psi
Using 1 inch SCH 40 PVC pipe.

Elevation head worst case scenario with the pump placed 6 feet below the ground surface in the pump tank.

Pressure head h_p= 2.31 ft per psi = 35*2.31 = 80.85 ft

Friction loss

Friction loss of the supply line

$h_f = 10.46 * 100 * (((7.7/150)^{1.852})/(1.033)^{4.871}) = 3.65$ ft

Friction loss of the longest lateral

$h_f = 10.46 * 55 * (((5.9/150)^{1.852})/(1.033)^{4.871}) = 2.19$ ft

Friction loss through fittings of the longest lateral (2 tees, 1 elbow)

Equivalent length of straight run pipe for 2 tees = 12 ft
Equivalent length of straight run pipe for 1 elbow = 2.5 ft
Total length = 14.5 ft

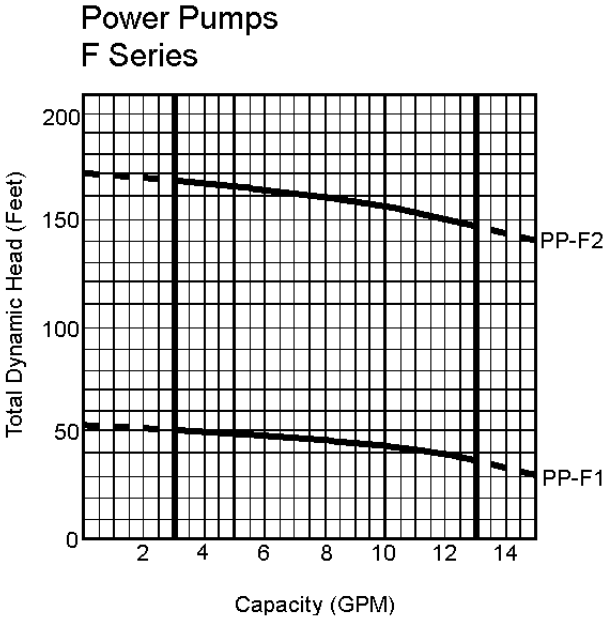
$h_f = 10.46 * 14.5 * (((5.9/150)^{1.852})/(1.033)^{4.871}) = 0.32$ ft

Friction loss = 3.65 ft + 2.19 ft + 0.32 = 6.16 ft

TDH = Elevation head + Pressure head + Friction loss

TDH = 6 ft + 80.85 ft + 6.16 ft = 93.01 ft, Say 93 ft

8. Select a pump based on the system operating curve.



Select pump, Option 1:
With the flow rate of 5.9 gpm at 96 ft TDH, the appropriate choice of pump would be Model PP-F2.

Select pump, Option 2:
With the flow rate of 7.7 gpm at 93 ft TDH, the appropriate choice of pump would be Model PP-F2.

9. Evaluate application rates based on operating curve, runtime, and heads selected.

Selection of Spray Heads, Example, Option 1:

- 3,750 square feet required
- Select 2 spray heads
  One SF – 1 spray head at 35 psi, 25 ft radius, 1964 ft^2.
  One SF – 2 spray head at 35 psi, 30 ft radius, 2463 ft^2.
- Total Area = 4,427 ft^2.

Check for uniform application, Option 1:

- One SF – 1 spray head at 35 psi, 25 ft radius, 1964 ft^2, 1.3 gpm flow rate.

One SF – 2 spray head at 35 psi, 30 ft radius, 2463 ft^2, 4.1 gpm flow rate.

- Total flow 240 gal./day. Flow 5.9 gpm, Run time = 240 gal./5.9 gpm = 40 minutes
- SF – 1 = 40 minutes x 1.3 gpm = 52 gal.
- SF – 2 = 40 minutes x 4.1 gpm = 164 gal.
- SF – 1 loading rate = 52 / 1964 = 0.027 gal./ft^2./d
- SF - 2 loading rate = 164 / 2463 = 0.067 gal./ft^2/d
- Design rate = 0.064 g / ft^2./d

Selection of Spray Heads, Option 2:

- 3,750 ft^2 required
- Select 3 spray heads
  Two SF – 1 spray heads at 35 psi, 25 ft radius, 1964 ft^2, operated on a half-circle basis
  One SF – 2 spray head at 35 psi, 28 ft radius, 2463 ft^2.
- Total Area = 4,427 ft^2.

Check for uniform application, Option 2:

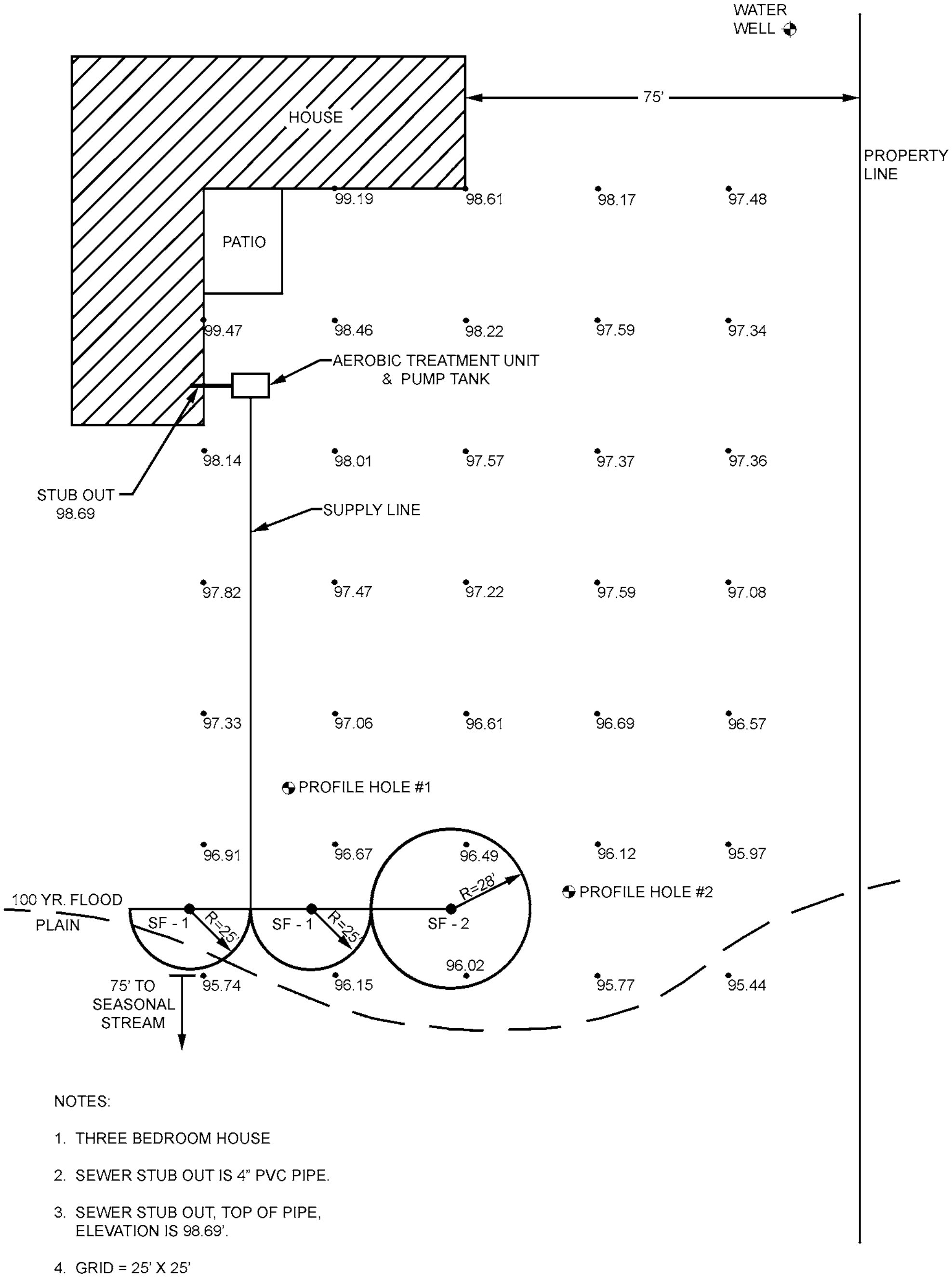
- Two SF – 1 spray heads at 35 psi, 25 ft radius, 1964 ft^2 total, each area 982 ft^2, 1.8 gpm flow rate each for total flow of 3.6 gpm.
- One SF – 2 spray head at 35 psi, 28 ft radius, 2463 ft^2, 4.1 gpm flow rate.
- Total flow 240 gal./day. Flow 7.7 gpm, Run time = 240 gal./7.8 gpm = 32 minutes
- SF – 1 = 32 minutes x 1.8 gpm = 58 gal.
- SF – 2 = 32 minutes x 4.1 gpm = 131 gal.
- SF – 1 loading rate = 58 / 982 = 0.059 gal./ ft^2/d
- SF – 2 loading rate = 131 / 2463 = 0.053 gal./ft^2/d
- Design rate = 0.064 gal./ft^2/d

From this we conclude that Option 2 should be used because in Option 1 the SF – 2 nozzle's application rate is larger than the design rate of 0.064 gal./ft^2/d.

10. Determine the pump tank size based on pump, flow, and design constraints.

Since the system will be dosed at night the dosing volume of the pump tank is 240 gallons. There is also an operational volume in order for the pump to operate. The alarm volume of the pump tank must be 1/3 of the daily flow. So for a 240 gallon a day system the alarm volume must be 80 gallons.

Use a 500 gallon pump tank with an inner diameter of 5 ft. The operating level of the pump is 14 inches. Then the operating volume of the tank would be 171 gallons, dosing volume of 240 gallons, and the alarm volume of 80 gallons, for a total volume needed of 491 gallons.



NOTES:

1. THREE BEDROOM HOUSE
2. SEWER STUB OUT IS 4" PVC PIPE.
3. SEWER STUB OUT, TOP OF PIPE, ELEVATION IS 98.69'.
4. GRID = 25' X 25'

Figure 4.2: Final design layout for Option 2.

Municipal Systems

Most of the design parameters for designing municipal spray dispersal system are the same as designing an onsite wastewater treatment system. The differences include:

- Application Rate: The application rate of a municipal system is usually based on the evapotranspiration rate of the vegetation that is grown in the area.

- Vegetation: The vegetation grown under a municipal spray dispersal system may be harvested and sold for profit, while vegetation at onsite systems is typically part of the landscape of the facility and the amount of water applied is only supplemental. Different vegetations include pasture grasses, forage crops, row crops, and timber.
- Vegetation management: The different types of vegetation and reasons for growing the vegetation results in different management schemes. Special attention should be paid to the down time of the different spray dispersal zones for conducting crop management practices, resulting in increased storage or land area.
- Piping approaches: The type of vegetation and vegetative management of the system will determine the approach for distributing the water to the spray heads. For plans that require frequent access, easily removable or mobile systems are used, while a more permanent solution can be used on systems that are not accessed frequently.
- Storm water control may need to be incorporated into the design. Rainfall running off the fields need to be managed to prevent erosion problems.
- Monitoring for nutrients, soil moisture, and evapotranspiration: Municipal systems are limited ultimately by the application rate of nutrients in the wastewater. Monitoring must also include soil moisture, because the system can not be dosed when the soil is saturated. If water is applied during saturated conditions, surface runoff could contaminate surface water. ET is monitored to maximize the amount of water that can be applied to the application area and to maximize growth of the cover crop.
- Salinity management: A portion of water applied to a municipal system is allowed to deep percolate. This deep percolation allows leaching of salts that would normally remain near the soil surface.

Spray Dispersal

Chapter 5

Operation and Maintenance Considerations

Systems should be properly maintained and operated at all time to ensure proper effluent treatment and application, and minimization of runoff from the system. Proper operation and maintenance is accomplished with:

- Routine inspections of the treatment and dispersal system.
- Cleaning of all filters in the system.
- Inspection of the system during dispersal.
- Prompt response to alarms or complaints.
- Complete records of maintenance visits, repairs made, and list of parts used in the system.
- Suitable vegetation.
- Restriction of traffic across the system except during installation and normal maintenance.

Application Timing

The timing of the application to the dispersal system depends on the type of controls used. If an "on-demand" controlling system is used the timing of the application depends on the habits of the facility. Once a set volume of effluent enters the pump tank the float is triggered to discharge effluent. If a surge flow triggers the float, the dose of effluent will be larger than the designed dose. For example, if the float is triggered by the first couple of gallons from the emptying of a bathtub then the dose could be forty or more gallons larger than the design dose. This over-dosing could cause runoff from the site. If the system is set up to "night dose", a photocell is used to determine that it is night time before the system doses. Night dosing can be used to limit the possibility of human contact with effluent being discharged. In some cases, night dosing allows for shortened set back distances from property lines depending on state regulations.

When other control methods are used they can be set up to discharge a set volume of water to the system to promote infiltration into the soil to reduce the potential of runoff. When spray dispersal is used by municipalities, the effluent is discharged to meet the ET of the cover crop. During wet seasons or when the field is fallow the effluent has to be stored until needed. For these systems, continuous management is necessary to ensure proper application is obtained. Additionally, during a rain event, the system needs to be shut down to prevent runoff.

Vegetation Management

All spray dispersal system should have a good vegetative cover over the dispersal field. The vegetation covering the dispersal field needs to be properly managed to be effective in the final treatment of the effluent. Spray dispersal systems are designed based on the ET or nutrient loading of the cover crop in the dispersal field and if the cover crop is in poor or stressed the ET or nutrient uptake is reduced. For onsite systems, the cover grass should be mowed to prevent obstructions in the path of the spray head. These obstructions reduce application uniformity of the system. Other obstructions such as trees and shrubs should be removed if they are within 10 ft of the spray head, or during the design of the system the spray heads should be located away from trees and large shrubs. For most onsite systems, application rate is usually set for the month with the lowest ET, so that during time of high ET, the dispersal field will not be covered by lush green grass. During this time of the year, the effluent is just a supplemental water source and additional water is needed to produce lush green grass. If the cover grass goes dormant during the winter the area should be over seeded with a winter grass to maintain the ET of the system. In the case that the cover crop will be maintained in a limited state the spray heads should be placed higher to prevent tall grass from obstructing the spray pattern.

For municipal systems, cover crop is usually highly maintained and harvested. The harvesting of the cover crop adds another aspect to consider, which is the withdraw period that is needed before the crop can be harvested. Also, the field must to be dry to get equipment into the field to harvest the crop.

References

Allen, Richard G., Luis S. Pereira, Dirk Reas, Martin Smith. 1998. Crop Evapotranspiration: guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper No. 56. FAO - Food and Agriculture Organization of the United Nations Rome.

Choate, Richard B. 1994. Turf Irrigation Manual: The Complete Guide to Landscape Irrigation Design 5th ed. Dallas, Texas: Weather-matic.

Environmental Protection Agency (EPA). 2002. Onsite Wastewater Treatment System Manual. Office of Water. EPA/625/R-00/008.

K-Rain Manufacturing Corp. 1999. Innovation and Performance. Riviera Beach, Florida.

Midwest Plan Service (MWPS), 1993. Livestock Waste Facilities Handbook. Iowa State University, Ames, Iowa, MWPS-18.

Appendix A: Evapotranspiration

(This information was copied from Crop Evapotranspiration, FAO Irrigation and Drainage Paper No. 56 covering the Penman-Monteith equation)

Evapotranspiration (ET) is the combined effects of soil evaporation and transpiration of plants. Soil evaporation is the rate at which water is transformed from a liquid to a gas in the soil. Transpiration is the rate at which liquid water is absorbed by plant roots, transported through the plant and discharged into the atmosphere as water vapor.

There are several methods used to calculate the ET for a given area. These methods differ by the data requirements and level of sophistication.

The FAO Penman-Monteith method uses temperature, humidity, wind and solar radiation for weekly, ten-day or monthly calculations of ET_o for a given location

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34 u_2)} \tag{1}$$

where:

ET_o= evapotranspiration for grass reference crop (mm/day)
R_n= net radiation at crop surface (MJ/day/m^2)
G= soil heat flux density (MJ/day/m^2)
T= mean daily air temperature at 2m height (^oC)
u_2=wind speed at 2m height(m/s)
e_s= saturation vapor pressure (kPa)
e_a= actual vapor pressure (kPa)
e_s- e_a = saturation vapor pressure deficit(kPa)
D=slope of vapor pressure curve (kPa/^oC)
g= psychrometric constant (kPa/^oC)

Apart from the site location, the FAO Penman-Monteith equation requires air temperature, humidity, radiation and wind speed data for daily, weekly, ten-day or monthly calculations. It is important to verify the units in which the weather data are reported.

Location

Altitude above sea level (m) and latitude (degrees north or south) of the location should be specified. These data are needed to adjust some weather parameters for the local average value of atmospheric pressure (a function of the site elevation above mean sea level) and to compute extraterrestrial radiation (R_a) and, in some cases, daylight hours (N). In the calculation procedures for R_a and N, the latitude is expressed in radian (i.e., decimal degrees times $\pi/180$).

A positive value is used for the northern hemisphere and a negative value for the southern hemisphere.

Temperature

The (average) daily maximum and minimum air temperatures in degrees Celsius (^{o}C) are required. Where only (average) mean daily temperatures are available, the calculations can still be executed but some underestimation of ET_o will probably occur due to the non-linearity of the saturation vapor pressure - temperature relationship. Using mean air temperature instead of maximum and minimum air temperatures yields a lower saturation vapor pressure e_s, and hence a lower vapor pressure difference (e_s - e_a), and a lower reference evapotranspiration estimate.

Humidity

The (average) daily actual vapor pressure, e_a, in kilopascals (kPa) is required. The actual vapor pressure, where not available, can be derived form maximum and minimum relative humidity (%), psychrometric data (dry and wet bulb temperatures in ^{o}C) or dewpoint temperature (^{o}C).

Radiation

The (average) daily net radiation is expressed in megajoules per square meter per day (MJ $^{-2}$ day^{-1}) is required. Net radiation in not commonly available but can be derived from the (average) shortwave radiation measured with a phranometer or from the (average) daily actual duration of bright sunshine (hours per day) measured with a (Campbell-Stokes) sunshine recorder.

Wind speed

The (average) daily wind speed in meters per second (m s^{-1}) measured at 2 m above the ground level is required. It is important to verify the height at which wind speed is measured, as wind speeds measured at different heights above the soil surface differ.

Missing climatic data

Situations might occur where data for some weather variables are missing. The use of an alternative ET_o calculation procedure, requiring limited meteorological parameters, should be avoided. It is recommended that ET_o is calculated using the standard FAO Penman-Monteith method after resolving problems of the missing data. Differences between ET_o values obtained with the FAO Penman-Monteith equation with limited data is smaller than the used of an alternative ET_o equation.

Even where the data set contains only maximum and minimum air temperature it is still possible to obtain reasonable estimates of ten-day or monthly ET_o with the FAO Penman-Monteith equation. Radiation data can be derived from the air temperature difference, or, along with wind speed and humidity data, can be obtained from nerarby weather stations. Humidity data can be estimated from daily minimum air temperature.

The procedures for estimating missing data should be validated at the regional level. This can be done for weather stations with full data sets by comparing ET_o calculated with full and with limited data sets. The ratio should be close to one.

Meteorological factors determining ET

The meteorological factors determining evapotranspiration are weather parameters which provide energy for vaporization and remove water vapor from the evaporating surface.

Solar radiation

The evapotranspiration process is determined by the amount of energy available to vaporize water. Solar radiation is the largest energy source and is able to change large quantities of liquid water into water vapor. The potential amount of radiation that can reach the evaporating surface is determined by its location and time of the year. Due to differences in the position of the sun, the potential radiation differs at various latitudes and in different seasons. The actual solar radiation reaching the evaporating surface depends on the turbidity of the atmosphere and the presence of clouds which reflect and absorb major parts of the radiation. When assessing the effect of solar radiation on evapotranspiration, one should also bear in mind that not all available energy is used to vaporize water. Part of the solar energy is used to heat up the atmosphere and the soil profile.

Air temperature

The solar radiation absorbed by the atmosphere and the heat emitted by the earth increase the air temperature. The sensible heat of the surrounding air transfers energy to the crop and exerts as such a controlling influence on the rate of evapotranspiration. In sunny, warm weather the loss of water by evapotranspiration is greater than in cloudy and cool weather.

Air humidity

While the energy supply from the sun and surrounding air is the main driving force for the vaporization of water, the difference between the water vapor pressure at the evapotranspiring surface and the surrounding air is the determining factor for the vapor removal. Well-watered fields in hot dry arid regions consume large amounts of water due to the abundance of energy and the desiccating power of the atmosphere. In humid tropical regions, notwithstanding the high energy input, the high humidity of the air will reduce the evapotranspiration demand. In such an environment, the air is already close to saturation, so that less additional water can be stored and hence the evapotranspiration rate is lower than in arid regions.

Wind speed

The process of vapor removal depends to a large extent on wind and air turbulence which transfers large quantities of air over the evaporating surface. When vaporizing water, the air above the evaporating surface becomes gradually saturated with water vapor. If this air is not continuously replaced with drier air, the driving force for water vapor removal and the evapotranspiration rate decreases.

The evapotranspiration demand is high in hot dry weather due to the dryness of the air and the amount of energy available as direct solar radiation and latent heat. Under these circumstances, much water vapor can be stored in the air while wind may promote the transport of water allowing more water vapor to be taken up. On the other hand, under humid weather conditions, the high humidity of the air and the presence of clouds cause the evapotranspiration rate to be lower. The drier the atmosphere, the larger the effect on ET and the greater the slope of the curve. For humid conditions, the wind can only replace saturated air with slightly less saturated air and remove heat energy. Consequently, the wind speed affects the evapotranspiration rate to a far lesser extent than under arid conditions where small variations in wind speed may result in larger variations in the evapotranspiration rate.

Atmospheric parameters

Several relationships are available to express climatic parameters. The effect of the principal weather parameters on evapotranspiration can be assessed with the help of these equations. Some of the relationships require parameters which express a specific characteristic of the atmosphere. Before studying the four principal weather parameters, some atmospheric parameters will be discussed.

Atmospheric pressure (P)

The atmospheric pressure, P, is the pressure exerted by the weight of the earth's atmosphere. Evaporation at high altitudes is promoted due to low atmospheric pressure as expressed in the psychrometric constant. The effect is, however, small and in the calculation procedures, the average value for a location is sufficient. A simplification of the ideal gas law, assuming 20°C for a standard atmosphere, can be employed to calculate P:

$$P = 101.3\left(\frac{293 - 0.0065z}{293}\right)^{5.26} \quad (2)$$

where:

P = atmospheric pressure [kPa],
z = elevation above sea level [m],

Values for atmospheric pressure as a function of altitude are given in Table A.2

Latent heat of vaporization (λ)

The latent heat of vaporization, λ, expresses the energy required to change a unit mass of water from liquid to water vapor in a constant pressure and constant temperature process. The value of the latent heat varies as a function of temperature. At a high temperature, less energy will be required than at lower temperatures. As λ varies only slightly over normal temperature ranges a single value of 2.45 MJ kg^{-1} is taken in the simplification of the FAO Penman-Monteith equation. This is the latent heat for an air temperature of about 20°C.

Psychrometric constant (γ)

The psycrometric constant, γ, is given by:

$$\gamma = \frac{c_p\, P}{\varepsilon \lambda} = 0.665 \times 10^{-3} P \qquad (3)$$

where:

γ = psycrometric constant [kPa °C^{-1}],
P = atmospheric presure [kPa],
λ = latent heat of vaporization, 2.45 [MJ kg^{-1}],
cp = specific heat at constant pressure, 1.013 10^{-3} [MJ kg^{-1} °C^{-1}],
ε = ratio molecular weight of water vapor/dry air = 0.622.

The specific heat at constant pressure is the amount of energy required to increase the temperature of a unit mass of air by one degree at constant pressure. Its value depends on the composition of the air, i.e., on its humidity. For average atmospheric conditions a value $c_p = 1.013\ 10^{-3}$ MJ kg^{-1} °C^{-1} can be used. As an average atmospheric pressure is used for each location (Equation 2), psychrometric constant is kept constant for each location. Values for the psychrometric constant as a function of altitude are given in Table A.3

Air temperature

Agrometerology is concerned with the air temperature near the level of the crop canopy. In traditional and modern automatic weather stations the air temperature is measured inside shelters with World Meteorological Organization (WMO) standards at 2 m above the ground. The shelters are designed to protect the instruments from direct exposure to solar heating. The louvered construction allows free air movement around the instruments. Minimum and maximum thermometers record the minimum and maximum air temperature over a 24-hour period.

Due to the non-linearity of humidity data required in the FAO Penman-Monteith equation, the vapor pressure for a certain period should be computed as the mean between the vapor pressure at the daily maximum and minimum air temperatures of that period. The daily maximum air temperature (T_{max}) and daily minimum air temperature (T_{min}) are, respectively, the maximum and minimum air temperature observed during the 24-hour period, beginning at midnight. T_{max} and T_{min} for longer periods such as weeks, 10-day's or months are obtained by dividing the sum of the respective daily values by the number of days in the period. The mean daily air temperature (T_{mean}) is only employed in the FAO Penman-Monteith equation to calculate the slope of the saturation vapor pressure curves (Δ) and the impact of mean air density (P_a) as the effect of temperature variations on the value of the climatic parameter is small in these cases. For standardization, T_{mean} for 24-hour periods is defined as the mean of the daily maximum (T_{max}) and minimum temperatures (T_{min}) rather than as the average of hourly temperature measurements.

$$T_{mean} = \frac{T_{max} + T_{min}}{2} \qquad (4)$$

The temperature if given in degrees Celsius (°C) or Fahrenheit (°F). In some calculation procedures, temperature is required in Kelvin (K) which can be obtained by adding 273.16 to the temperature expressed in degrees Celsius (in practice K = °C + 273.16). The Kelvin and Celsius scale have the same scale interval.

Air humidity

The water content of the air can be expressed in several ways. In agrometeorology, vapor pressure, dewpoint temperature and relative humidity are common expressions to indicate air humidity.

Vapor pressure

Water vapor is a gas and its pressure contributes to the total atmospheric pressure. The amount of water in the air is related directly to the partial pressure exerted by the water vapor in the air and is therefore a direct measure of the air water content.

In standard S.I. units, pressure is expressed in pascals (Pa). A pascal refers to a relatively small force (1 newton) applied on a relatively large surface (1 m^2), multiples of the basic unit are often used.

When air is enclosed above an evaporating water surface, an equilibrium is reached between the water molecules escaping and returning to the water reservoir. At that moment, the air is said to be saturated since it cannot store any extra water molecules. The corresponding pressure is called the saturation vapor pressure ($e^o(T)$). The number of water molecules that can be stored in the air depends on the temperature (T). The higher the air temperature, the higher the storage capacity, the higher its saturation vapor pressure.

The slope of the saturated vapor pressure curve changes exponentially with temperature. At low temperatures, the slope is small and varies only slightly as the temperature rises. At high temperatures, the slope is large and small changes in T result in large changes in slope. The slope of the saturation vapor pressure curve, Δ, is an important parameter in describing vaporization and is required in the equations for calculating ET_o from climatic data.

The actual vapor pressure (e_a) is the vapor pressure exerted by the water in the air. When the air is not saturated, the actual vapor pressure will be lower than the saturation vapor pressure. The difference between the saturation and actual vapor pressure is called the vapor pressure deficit or saturation deficit and is an accurate indicator of the actual evaporative capacity of the air.

Dewpoint temperature

The dewpoint temperature is the temperature to which the air needs to be cooled to make the air saturated. The actual vapor pressure of the air is the saturation vapor pressure at the dewpoint temperature. The drier the air, the larger the difference between the air temperature and dewpoint temperature.

Relative humidity

The relative humidity (RH) expresses the degree of saturation of the air as a ratio of the actual (e_a) to the saturation ($e^o(T)$) vapor pressure at the same temperature (T):

$$RH = 100\frac{e_a}{e^o(T)} \qquad (5)$$

Relative humidity is the ratio between the amount of water the ambient air actually holds and the amount it could hold at the same temperature. It is dimensionless and is commonly given as a percentage. Although the actual vapor pressure might be relatively constant throughout the say, the relative humidity fluctuates between a maximum near sunrise and a minimum around early afternoon. The variation of the relative humidity is the result of the fact that the saturation vapor pressure is determined by the air temperature. As the temperature changes during the day, the relative humidity also changes substantially.

Measurement

It is not possible to directly measure the actual vapor pressure. The vapor pressure is commonly derived form relative humidity or dewpoint temperature.

Relative humidity is measured directly with hygrometers. The measurement is based on the nature of some material such as hair, which changes its length in response to changes in air humidity, or using a capacitance plate, where the electric capacitance changes with RH. Vapor pressure can be measured indirectly with a psychrometer which measure the temperature difference between two thermometers, the so-called dry and wet bulb thermometers. The dry bulb thermometer measures the temperature of the air. The bulb of the wet bulb thermometer is covered with a constantly saturated wick. Evaporation of water from the wick, requiring energy, lowers the temperature of the thermometer. The drier the air, the larger the evaporative cooling and the larger the temperature drop. The difference between the dry and wet bulb temperatures is called the wet bulb depression and is a measure of the air humidity.

The dewpoint temperature is measured with dewpoint meters. The underlying principle of some types of apparatus is the cooling of the ambient air until dew formation occurs. The corresponding temperature is the dewpoint temperature.

Relative humidity and dewpoint temperature data are notoriously plagues by measurement errors.

Calculation procedures

Mean saturation vapor pressure (es)

As saturation vapor pressure is related to air temperature, it can be calculated form the air temperature. The relationship is expressed by:

$$e^{o}(T) = 0.6108 \exp\left[\frac{17.27\,T}{T + 237.3}\right] \qquad (6)$$

where:

$e^{o}(T)$ = saturation vapor pressure at the air temperature T [kPa],
T = air temperature [°C],
exp[..] = 2.7183 (base of natural logarithm) raised to the power [..].

Values of saturation vapor pressure as a function of air temperature are given in Table A.4. Due to the non-linearity of the above equation, the mean saturation vapor pressure for a day, week, decade or month should be computed as the mean between the saturation vapor pressure at the mean daily maximum and minimum air temperatures for that period:

$$e_s = \frac{e^{o}(T_{max}) + e^{o}(T_{min})}{2} \qquad (7)$$

Using mean air temperature instead of daily minimum and maximum temperatures results in lower estimates for the mean saturation vapor pressure. The corresponding vapor pressure deficit (a parameter expressing the evaporating power of the atmosphere) will also be smaller and the result will be some underestimation of the reference crop evapotranspiration. Therefore, the mean saturation vapor pressure should be calculated as the mean between the saturation vapor pressure at both the daily maximum and minimum air temperature.

Slope of saturation vapor pressure curve (Δ)

For the calculation of evapotranspiration, the slope of the relationship between saturation vapor pressure and temperature, Δ, is required. The slope of the curve (Figure 11) at a given temperature is given by:

$$\Delta = \frac{4098\left[0.6108 \exp\left(\frac{17.27\,T}{T + 237.3}\right)\right]}{(T + 237.3)^2} \qquad (8)$$

where:

Δ = slope of saturation vapor pressure curve at air temperature T [kPa $°C^{-1}$],
T = air temperature [°C]

exp[..] = 2.7183 (base of natural logarithm) raised to the power [..].

Values of slope Δ for different air temperatures are given in Table A.5. In the FAO Penman-Monteith equation, where Δ occurs in the numerator and denominator, the slope of the vapor pressure curve is calculated using mean air temperature (Equation 4).

Actual vapor pressure (e_a) derived from dewpoint temperature

As the dewpoint temperature is the temperature to which the air needs to be cooled to make the air saturated, the actual vapor pressure **(e_a)** is the saturation vapor pressure at the dewpoint temperature (T_{dew}) [°C], or:

$$e_a = e^o(T_{dew}) = 0.6108 \exp\left[\frac{17.27\,T_{dew}}{T_{dew} + 237.3}\right] \quad (9)$$

Actual vapor pressure (e_a) derived form psychrometric data

The actual vapor pressure can be determined for the difference between the dry and wet bulb temperatures, the so-called wet bulb depression. The relationship is expressed by the following equation:

$$e_a = e^o(T_{wet}) - \gamma_{psy}(T_{dry} - T_{wet}) \quad (10)$$

where:

e_a = actual vapor pressure [kPa],
$e^o(T_{wet})$ = saturation vapor pressure at wet bulb temperature [kPa],
γ_{psy} = psychrometeric constant of the instrument [kPa $°C^{-1}$],
T_{dry}-T_{wet} = wet bulb depression, with T_{dry} the dry bulb and T_{wet} the wet bulb temperature [°C].

The psychrometric constant of the instrument is given by:

$$\gamma_{psy} = a_{psy} P \quad (11)$$

where a_{psy} is a coefficient depending on the type of ventilation of the wet bulb [$°C^{-1}$], and P is the atmospheric pressure [kPa]. The coefficient a_{psy} depends mainly on the design of the psychrometer and rate of ventilation around the wet bulb. The following values are used:

a_{psy} = 0.000662 for ventilated (Asmann type) psychrometers, with an air movement of some 5 m/s, 0.000800 for natural ventilated psychrometers (about 1 m/s), 0.001200 for non-ventilated psychrometers installed indoors.

Actual vapor pressure (e_a) derived form relative humidity data

The actual vapor pressure can also be calculated from the relative humidity. Depending on the availability of the humidity data, different equations should be used.

- **For RH_{mas} and RH_{min}:**

$$e_a = \frac{e^o(T\ min)\frac{RH_{max}}{100} + e^o(T\ max)\frac{RH_{min}}{100}}{2} \tag{12}$$

where:

e_a = actual vapor pressure [kPa],
e^o (T_{min}) = saturation vapor pressure at daily minimum temperature [kPa],
e^o (T_{max}) = saturation vapor pressure at daily maximum temperature [kPa],
RH_{max} = maximum relative humidity [%],
RH_{min} = minimum relative humidity [%].

For periods of a week, ten days or a month, RH_{max} and RH_{min} are obtained by dividing the sum of the daily values by the number of days in that period.

- **For RH_{max}:**

When using equipment where errors in estimating RH_{min} can be large, or when RH data integrity are in doubt, then one should use only RH_{max}:

$$e_a = e^o(T_{min})\frac{RH_{max}}{100} \tag{13}$$

- **For RH_{mean}:**

In the absence of RH_{max} and RH_{min}, another equation can be used to estimate e_a:

$$e_a = \frac{RH_{mean}}{100}\left[\frac{e^o(T_{max}) + e^o(T\ min)}{2}\right] \tag{14}$$

where RH_{mean} is the mean relative humidity, defined as the average between RH_{max} and RH_{min}. However, Equation 14 is less desirable than are Equations 13 and 12.

Vapor pressure deficit (e_s - e_a)

The vapor pressure deficit is the difference between the saturation (e_s) and the actual vapor pressure (e_a) for a given time period. For time periods such as a week, ten days or a month e_s is computed form Equation 7 using the T_{max} and T_{min} averaged over the time period and similarly the e_a is computed, using average measurements over the period. As stated above, using mean air temperature and not T_{max} and T_{min} in Equation 7 results in a lower estimate of e_s, thus in a lower vapor pressure deficit and hence an underestimation of the ET_o. When desired, e_s and e_a for long time periods can also be calculated as averages of values computed for each day of the period.

Radiation

Extraterrestrial radiation (R_a)

The radiation striking a surface perpendicular to the sun's rays at the top of the earth's atmosphere, called the solar constant, is about 0.082 MJ m^{-2} min^{-1}. The local intensity of radiation is, however, determined by the angle between the direction of the sun's rays and the normal to the surface of the atmosphere. This angle will change during the day and will be different at different latitudes and in different seasons. The solar radiation received at the top of the earth's atmosphere on a horizontal surface is called the extraterrestrial (solar) radiation, R_a.

If the sun is directly overheard, the angle of incidence is zero and the extraterrestrial radiation is 0.0820 MJ m^{-2} min^{-1}. As seasons change, the position of the sun, the length of the day and, hence, R_a change as well. Extraterrestrial radiation is thus a function of latitude, date and time of day.

Solar or shortwave radiation (R_s)

As the radiation penetrates the atmosphere, some of the radiation is scattered, reflected or absorbed by the atmospheric gases, clouds and dust. The amount of radiation reaching a horizontal plane is known as the solar radiation, R_s. Because the sun emits energy by means of electromagnetic waves characterized by short wavelengths, solar radiation is also referred to as shortwave radiation.

For a cloudless day, R_s is roughly 75% of extraterrestrial radiation. On a cloudy day, the radiation is scattered in the atmosphere, but even with extremely dense cloud cover, about 25% of the extraterrestrial radiation may still reach the earth's surface mainly as diffuse sky radiation. Solar radiation is also known as global radiation, remaining that is it the sum of direct shortwave radiation from the sun and diffuse sky radiation from all upward angles.

Relative shortwave radiation (R_s /R_{so})

The relative shortwave radiation is the ratio of the solar radiation (R_s) to the clear-sky solar radiation (R_{so}). R_s is the solar radiation that actually reaches the earth's surface in a given period, while R_{so} is the solar radiation that would reach the same surface during the same period but under cloudless conditions.

The relative shortwave radiation is a way to express the cloudiness of the atmosphere; the cloudier the sky the smaller the ratio. The ratio varies between about 0.33 (dense cloud cover) and 1 (clear sky). In the absence of a direct measurement of R_n, the relative shortwave radiation is used in the computation of the net longwave radiation.

Relative sunshine duration (n/N)

The relative sunshine duration is another ratio that expresses the cloudiness of the atmosphere. It is the ratio fo the actual duration of sunshine, n, to the maximum possible duration of sunshine or daylight hours N. In the absence of any clouds, the actual duration of sunshine is equal to the daylight hours (n = N) and the ratio is one, while on cloudy days n and consequently the ratio may be zero. In the absence of a direct measurement of R_s, the relative sunshine duration, n/N, is often used to derive solar radiation from extraterrestrial radiation.

As with extraterrestrial radiation, the daylength N depends on the position of the sun and is hence a function of latitude and date.

Albedo (α) and the net solar radiation (R_{ns})

A considerable amount of solar radiation reaching the earth’s surface is reflected. The fraction, α, of the solar radiation reflected by the surface is known as the albedo. The albedo is highly variable for different surface s and for the angle of incidence or slope of the ground surface. It may be as large as 0.95 for freshly fallen snow and as small as 0.05 for a wet bare soil. A green vegetation cover has an albedo of about 0.20-0.25. For the green grass reference crop, α is assumed to have a value of 0.23.

The net solar radiation, R_{ns}, is the fraction of the solar radiation R_s that is not reflected from the surface. Its value is $(1-\alpha)R_s$.

Net longwave radiation (R_{nl})

The solar radiation absorbed by the earth is convereted to heat energy. By several processes, including emission of radiation, the earth loses this energy. The earth, which is at a much lower temperature than the sun, emits radiative energy with wavelengths longer than those from the sun. Therefore, the terrestrial radiation is referred to as longwave radiation. The emitted longwave radiation ($R_{1,up}$) is absorbed by the atmosphere or is lost into space. The longwave radiation received by the atmosphere ($R_{1,down}$) increases its temperature and, as a consequence, the atmosphere radiates energy of its own, as illustrated in Figure 15. Part of the radiation finds it way back to the earth’s surface. Consequently, the earth’s surface both emits and receives longwave radiation. The difference between outgoing and incoming longwave radiation is called the net longwave radiation, R_{nl}. As the outgoing longwave radiation is almost always greater than the incoming longwave radiation, R_{nl} represents an energy loss.

Net radiation (R_n)

The net radiation, R_n, is the difference between incoming and outgoing radiation of both short and long wavelengths. It is the balance between the energy absorbed, reflected and emitted by the earth’s surface or the difference between the incoming net shortwave (R_{ns}) and the net outgoing longwave (R_{nl}) radiation. R_n is normally positive during the daytime and negative during the nighttime. The total daily value for R_n is almost always positive over a period of 24 hours, except in extreme conditions at high latitudes.

Soil heat flux (G)

In making estimates of evapotranspiration, all terms of the energy balance should be considered. The soil heat flux, G, is the energy that is utilized in hearing the soil. G is positive when the soil is warming and negative when the soil is cooling. Although the soil heat flux is small compared to R_n and may often be ignored, the amount of energy gained or lost by the soil in this process should theoretically be subtracted or added to R_n when estimating evapotranspiration.

Units

The standard unit used in this handbook to express energy received on a unit surface per unit time is megajoules per square meter per day (MJ m^{-2} day^{-1}). In meterological bulletins other units might be used or radiation might even be expressed in units no longer accepted as standard S.I. units, such as calories cm^{-2} day^{-1}.

In the FAO Penman-Monteith equation (Equation 1), radiation expressed in MJ m^{-2} day^{-1} is converted to equivalent evaporation in mm day^{-1} by using a conversion factor equal to the inverse of the latent heat of vaporization ($1/\lambda = 0.408$):

$$\text{equivalent evaporation mm day}^{-1} = 0.408 \text{ x Radiation MJ m}^{-2} \text{ day-1} \qquad (15)$$

Common units used to express energy received on a unit surface per unit time, and conversion factors are summarized in Table A.1.

TABLE A.1 – Conversion factors for radiation

	multiplier to obtain energy received on a unit surface per unit time				equivalent evaporation mm day^{-1}
	MJ m^{-2} day^{-1}	J cm^{-2} day^{-1}	cal cm^{-2} day^{-1}	W m^{-2}	
1 MJ m^{-2} day^{-1}	1	100	23.9	11.6	0.408
1 cal cm^{-2} day^{-1}	4.1868 10^{-2}	4.1869	1	0.485	0.0171
1 W m^{-2}	0.0864	8.64	2.06	1	0.035
1 mm day^{-1}	2.45	245	58.5	28.4	1

Measurement

Solar radiation can be measured with pyranometers, radiometers or solarimeters. The instruments contain a sensor installed on a horizontal surface that measures the intensity of the total solar radiation, i.e., both direct and diffuse radiation form cloudy conditions. The sensor is often protected and kept in a dry atmosphere by a glass dome that should be regularly wiped clean.

Net longwave and net shortwave radiation can be measured by recording the difference in output between sensors facing upward and downward. In a net radiometer, the glass domes are replaced by polyethylene domes that have a transmission range for both shortwave and longwave radiation.

Where pyranometers are not available, solar radiation is usually estimated form the duration of bright sunshine. The actual duration of sunshine, n, is measured with a Campbell-Stokes sunshine recorder. This instrument records periods of bright sunshine by using a glass globe that act as a lens. The sun rays are concentrated at a focal point that burns a hole in a specially treated card mounted concentrically with a sphere. The movement of the sun changes the focal point throughout the day and a trace is drawn on the card. If the sun is obscured, the trace is interrupted. The hours of bright sunshine are indicated by the lengths of the line segments.

The quantity of heat conducted into the soil, G, can be measured with systems of soil heat flux plates and thermocouples or thermisters.

Calculation procedures

Extraterrestrial radiation for daily periods (R_a)

The extraterrestrial radiation, R_a, for each day of the year and for different latitudes can be estimated from the solar constant, the solar declination and the time of the year by:

$$R_a = \frac{24(60)}{\pi} G_{sc} d_r \left[\omega_s \sin(\varphi)\sin(\delta) + \cos(\varphi)\cos(\delta)\sin(\omega_s)\right] \quad (16)$$

where:

R_a = extraterrestrial radiation [MJ m^{-2} day^{-1}],
G_{sc} = solar constant = 0.0820 MJ m^{-2} day^{-1},
d_r = inverse relative distance Earth-Sun (Equation 18),
ω_s = sunset hour angle (Equation 20 or 21) [rad],
φ = latitude [rad] (Equation 17),
δ = solar declination (Equation 19) [rad].

R_a is expressed in the above equation in MJ m^{-2} day^{-1}. The corresponding equivalent evaporation in mm day^{-1} is obtained by multiplying R_a by 0.408 (Equation 15). The latitude, φ, expressed in radians is positive for the northern hemisphere and negative for the southern hemisphere. The conversion form decimal degrees to radians is given by:

$$[\text{Radians}] = \frac{\pi}{180}[\text{decimal degrees}] \quad (17)$$

The inverse relative distance Earth-Sun, d_r, and the solar declination, δ, are given by:

$$d_r = 1 + 0.033\cos\left(\frac{2\pi}{365}J\right) \quad (18)$$

$$\delta = 0.409\sin\left(\frac{2\pi}{365}J - 1.39\right) \quad (19)$$

Where J is the number of the day in the year between 1 (1 January) and 365 or 366 (31 December). Values for J for all days of the year and an equation for estimating J are given in Table A.6.

The sunset hour angle, ω_s, is given by:

$$\omega_s = \arccos\left[-\tan(\varphi)\tan(\delta)\right] \quad (20)$$

As the arccos function is not available in all computer languages, the sunset hour angle can also be computed using the arctan function:

$$\omega_s = \frac{\pi}{2} - \arctan\left[\frac{-\tan(\varphi)\tan(\delta)}{X^{0.5}}\right] \quad (21)$$

where:

$$X = 1 - \left[\tan(\varphi)\right]^2\left[\tan(\delta)\right]^{12}$$
$$\text{and } X = 0.00001 \quad \text{if } X \leq 0 \quad (22)$$

Values for R_a for different latitudes are given in Table A.7. These values represent R_a on the 15th day of each month. These values deviate from values that are averaged over each day of the month by less than 1% for all latitudes during non-frozen periods and are included for simplicity of calculation. These values deviate slightly from the values in the Smithsonian Tables. For the winter months in latitudes greater than 55° (N or S), the equations for R_a have limited validity. Reference should be made to Smithsonian Tables to assess possible deviations.

Extraterrestrial radiation for hourly or shorter periods (R_a)

For hourly or shorter periods the solar time angle at the beginning and end of the period should be considered when calculating R_a:

$$R_a = \frac{12(60)}{\pi} G_{sc}\, d_r\left[(\omega_2 - \omega_1)\sin(\varphi)\sin(\delta) + \cos(\varphi)(\sin(\omega_2) - \sin(\omega_1))\right] \quad (23)$$

where:

R_a = extraterrestrial radiation in the hour (or shorter) period [MJ m^{-2} $hour^{-1}$],
G_{sc} = solar constant = 0.0820 MJ m^{-2} min^{-1},
d_r = inverse relative distance Earth-Sun (Equation 18),
δ = solar declination [rad] (Equation 19),
φ = latitude [rad] (Equation 17),
ω_1 = solar time angle at beginning of period [rad] (Equation 24),
ω_2 = solar time angle at end of period [rad] (Equation 25).

The solar time angles at the beginning and end of the period are given by:

$$\omega_1 = \omega - \frac{\pi t_1}{24} \quad (24)$$

$$\omega_2 = \omega + \frac{\omega t_1}{24} \quad (25)$$

where: ω = solar time angle at midpoint of hourly or shorter period [rad],
t_1 = length of the calculation period [hour]:

i.e., 1 for hourly period or 0.5 for a 30-minute period.

The solar time angle at midpoint of the period is:

$$w = \frac{\pi}{12}\left[(t + 0.0667(L_z - L_m) + S_c) - 12\right] \quad (26)$$

where:

t = standard clock time at the midpoint of the period [hour]. For example for a period between 14.00 and 15.00 hours, t = 14.5,
L_z =longitude of the center of the local time zone [degrees west of Greenwich]. For example, L_z = 75, 90, 105 and 120° for the Eastern, Central, Rocky Mountain and Pacific time zones (United States) and L_z = 0° for Greenwich, 330° for Cairo (Egypt), and 255° for Bangkok (Thailand),
L_m =longitude of the measurement site [degrees west of Greenwich],
S_c = seasonal correction for solar time [hour].

Of course, $\omega < -\omega_s$ or $\omega > \omega_s$ from Equation 26 indicates that the sun is below the horizon so that, by definition, R_a is zero.

The seasonal correction for solar time is:

$$S_c = 0.1645\sin(2b) - 0.1255\cos(b) - 0.025\sin(b) \quad (27)$$

$$b = \frac{2\pi(J-81)}{364} \quad (28)$$

where J is the number of the day in the year.

Daylight hours (N)

The daylight hours, N, are given by:

$$N = \frac{24}{\pi}\omega_s \quad (29)$$

Where ω_s is the sunset hour angle in radians given by Equation 20 or 21. Mean values for N (15th day of each month) for different latitudes are given in Table A.8.

Solar radiation (R_s)

If the solar radiation, R_s, is not measured, it can be calculated with the Angstrom formula, which relates solar radiation to extraterrestrial radiation and relative sunshine duration:

$$R_s = \left(a_s + b_s\frac{n}{N}\right)R_a \quad (30)$$

where:

R_s = solar or shortwave radiation [MJ m^{-2} day^{-1}]
n = actual duration of sunshine [hour]
N = maximum possible duration of sunshine or daylight hours [hour]
n/N = relative sunshine duration [-]
R_a = extraterrestrial radiation [MJ m^{-2} day^{-1}]
a_s =regression constant, expressing the fraction of extraterrestrial radiation reaching the earth on overcast days (n = 0)
$a_s + b_s$ = fraction of extraterrestrial radiation reaching the earth on clear days (n = N)

R_s is expressed in the above equation in MJ m^{-2} day^{-1}. The corresponding equivalent evaporation in mm day^{-1} is obtained by multiplying R_s by 0.408 (Equation 15). Depending on atmospheric conditions (humidity, dust) and solar declination (latitude and month), the Angstrom values a_s and b_s will vary. Where not actual solar radiation data are available and no calibration has been carried out for improved a_s and b_s parameters, the values $a_s = 0.25$ and $b_s = 0.50$ are recommended.

The extraterrestrial radiation, R_a, and the daylight hours or maximum possible duration of sunshine, N, are given by Equations 11 and 24. Values for R_a and N for different latitudes are also listed in Tables A.7 and A.8. The actual duration of sunshine, n, is recorded with a Campbell Stokes sunshine recorder.

Clear-sky solar radiation (R_{so})

The calculation of the clear-sky radiation, R_{so}, when n = N, is required for computing net longwave radiation.

- **For near sea level or when calibrated values for a_s and b_s are available:**

$$R_{SO} = (a_S + b_S)R_a \quad (31)$$

where:

R_{so} = clear-sky solar radiation [MJ m^{-2} day^{-1}],
$a_s + b_s$ = fraction of extraterrestrial radiation reaching the earth on clear-sky days (n =N).

- **When calibrated values for a_s and b_s are not available:**

$$R_{so} = \left(0.75 + 2\ 10^{-5} z\right) R_a \quad (32)$$

where:

z = station elevation above sea level [m].