Appendix 3

Water-Harvesting Earthworks Calculations

List of Equations and Other Information

Box A3.1. Abbreviations, Conversions, and Constants for English and Metric Measurement Units

Note: * items are approximate

ABBREVIATIONS FOR EQUATIONS
sqrt = square root, which is a function on most calculators

ABBREVIATIONS FOR ENGLISH UNITS
inches = in
feet = ft
square feet = ft^2
cubic feet = ft^3
gallons = gal
acre = a
Fahrenheit = F

CONVERSIONS FOR ENGLISH UNITS
To convert cubic feet to gallons, multiply cubic feet by 7.48 gal/ft^3 *
To convert inches to feet, divide inches by 12 in/ft
1 acre = 43,560 square feet
1 square mile = 27,878,400 square feet

CONSTANTS
Ratio between a circle's diameter and its circumference is expressed as π = 3.14

ABBREVIATIONS FOR METRIC UNITS
millimeters = mm
centimeters = cm
meters = m
liters = l
hectare = ha
Celsius = C

CONVERSIONS FOR METRIC UNITS
To convert cubic centimeters to liters, divide cubic centimeters by 1,000

CONVERTING BETWEEN ENGLISH UNITS AND METRIC UNITS
To convert inches to millimeters, multiply inches by 25.4 mm/in *
To convert inches to centimeters, multiply inches by 2.54 cm/in *
To convert feet to meters, multiply feet by 0.30 m/ft *
To convert square feet to square meters, multiply square feet by 0.092 m^2/ft^2 *
To convert cubic feet to cubic meters, multiply cubic feet by 0.028 m^3/ft^3 *
To convert gallons to liters, multiply gallons by 3.79 liter/gal *
To convert acres to hectares, multiply acres by 0.404 a/ha *
To convert miles to kilometers, multiply miles by 1.6 km/mi *
To convert Fahrenheit (F) to Celsius (C) for actual indoor/outdoor temperature measure ("it's 70 degrees outside today"), subtract 32 from Fahrenheit temperature, multiply result by 5, then divide by 9.
To convert Fahrenheit (F) to Celsius (C) for temperature difference ("it's 20 degrees hotter today than yesterday"), multiply Fahrenheit by 5, then divide by 9.

Equation 1A.
Catchment Area of Rectangular Surface (English units)

length (ft) × width (ft) = catchment area (ft^2)

EXAMPLE:

A house measures 47 feet long by 27 feet wide at the drip line of the roof. Note that it does not matter whether the roof is flat or peaked: The roof dimensions at the drip line are the same. It is the "footprint" of the roof's drip line that matters.

47 ft × 27 ft = 1,269 ft^2

1,269 ft^2 = catchment area

If the roof consists of two or more rectangles, calculate the area for each rectangle and add together. Again, take the view of a falling raindrop, and only look at the "footprint" of the roof's drip line. Roof pitch cannot be seen from above and does not matter. With conical, octagonal, or other non-standard roof shapes, again calculate the area based on the drip line.

Equation 1B.
Catchment Area of Rectangular Surface (metric units)

length (m) × width (m) = catchment area (m^2)

EXAMPLE:

15 m × 9 m = 135 m^2

135 m^2 = catchment area

Again, all the considerations in Equation 1A will apply.

Equation 2A.
Catchment Area of Triangular Surface (right triangle)

Multiply the lengths of the two shorter sides of the triangle then divide by 2 = catchment area

EXAMPLE:

A triangular section of roof measures 9 feet by 12 feet by 15 feet. This is a right triangle, with the 90-degree angle between the 9-foot and 12-foot sides. Taking the measurements of the two shorter sides:

(9 ft × 12 ft) ÷ 2 = catchment area (ft^2)

108 ft^2 ÷ 2 = 54 ft^2

54 ft^2 = catchment area

Equation 2B.
Catchment Area of Triangular Surface (standard math formula)

Multiply the triangle's base times its height then divide by 2 = catchment area
where the base can be any side, and the height is measured perpendicularly from the base to the opposite vertex.

EXAMPLE:

You want to know the area of a triangular section of patio. The length of the section in front of you is 20 feet (triangle base) and you measure 4 feet perpendicularly to the opposite vertex of the triangle.

$(20\text{ ft} \times 4\text{ ft}) \div 2$ = catchment area (ft^2)
$80\text{ ft}^2 \div 2 = 40\text{ ft}^2$
40 ft^2 = catchment area

Equation 2C.
Catchment Area of Triangular Surface (Heron's formula)

This formula, attributed to Heron of Alexandria (first century A.D.), involves no trigonometry. It only needs the square root (sqrt) function found on most electronic or computer calculators. It may be useful when dealing with non-right triangles where you can measure (or know) all sides of the triangle.

Step 1: Determine the lengths of the sides of the triangle. These are a, b, c.

Step 2: Calculate s.
$(a + b + c) \div 2 = s$

Step 3: Calculate S, using:
$s \times (s - a) \times (s - b) \times (s - c) = S$

Step 4: Calculate the catchment area, which is the square root of S.
sqrt S = catchment area

Equation 3.
Catchment Area of Circular Surface

$\pi \times r^2$ = catchment area

Note: r = radius of the circle. A circle's radius is half its diameter.

EXAMPLE:

A circular roof has a 25 foot diameter. Divide the diameter by 2 to get the radius of 12.5 feet.
$\pi \times (12.5\text{ ft} \times 12.5\text{ ft})$ = catchment area (ft^2)
$3.14 \times 156.25\text{ ft}^2 = 490.6\text{ ft}^2$

490.6 ft^2 = catchment area

Box A3.2. Estimating Maximum Rainfall Runoff Using Rules of Thumb

ROUGH RULE OF THUMB FOR CALCULATING MAXIMUM RAINFALL RUNOFF VOLUME ON A CATCHMENT SURFACE (ENGLISH UNITS):

You can collect 600 gallons of water per inch of rain falling on 1,000 square feet of catchment surface.

ON THE REALLY BIG SCALE:

You can collect 27,000 gallons of water per inch of rain falling on 1 acre of catchment surface.

RULE OF THUMB FOR CALCULATING MAXIMUM RAINFALL VOLUME ON A CATCHMENT SURFACE (METRIC UNITS):

You can collect 1,000 liters of water per each 10 millimeters of rain falling on 100 square meters of catchment surface.

ON THE REALLY BIG SCALE:

You can collect 100,000 liters of water per 10 millimeters of rain falling on one hectare of catchment surface.

Box A3.3. Meteorological and Climate Resources

ONLINE RESOURCES

www.wrh.noaa.gov. This is the United States National Weather Service's website. Locate the weather stations closest to your site and find out their elevations. Download data from those stations that are most like your site.

ag.arizona.edu/azmet. Arizona Meteorological Network. Evaporation rates, prevailing winds, soil temperatures, and minimum/maximum temperatures are listed for various sites. For other states contact your local agricultural extension service for similar meteorological networks.

MISCELLANEOUS

The U.S. National Forest Service compiles data for remote weather stations, though the data is not as comprehensive or as standardized as the above two resources. However, for rural sites a Forest Service weather station may be closer to a given site than one monitored by other agencies.

Local airports, since they collect and record climatic data.

Rain gauge from a hardware or garden store with which to begin keeping precipitation records for your site.

Equation 4A.
Potential Volume of Runoff from a Roof or Other Impervious Catchment Area (English units)

$$\text{catchment area (ft}^2) \times \text{rainfall (ft)} \times 7.48\ \text{gal/ft}^3 = \text{maximum runoff (gal)}$$

Note: For a more realistic estimate, see Equation 5.

EXAMPLE CALCULATING ANNUAL RUNOFF:

Calculate the maximum gallons of rain running off the roof in an average year from a home that measures 47 feet long and 27 feet wide at the drip line of the roof. (In the example below, the roof dimensions at the drip line are included in the calculation; the catchment area is the same whether the roof is flat or peaked.) Rainfall in this location averages 10.5 inches per year, so you will divide this by 12 inches of rainfall per foot to convert inches to feet for use in the equation. (Note: You can use the same equation to calculate the runoff from a single storm, by simply using the rainfall from that storm instead of annual average rainfall in the equation.) Since the roof is a rectangular area, use the following calculation for catchment area:

$$(\text{length (ft)} \times \text{width (ft)}) \times \text{rainfall (ft)} \times 7.48\ \text{gal/ft}^3 = \text{maximum runoff (gal)}$$

$$(47\ \text{ft} \times 27\ \text{ft}) \times (10.5\ \text{in} \div 12\ \text{in/ft}) \times 7.48\ \text{gal/ft}^3 = \text{maximum runoff (gal)}$$

$$1{,}269\ \text{ft}^2 \times 0.875\ \text{ft} \times 7.48\ \text{gal/ft}^3 = 8{,}306\ \text{gal}$$

8,306 gal = maximum runoff

EXAMPLE CALCULATING RUNOFF FROM A SINGLE RAIN EVENT:

Calculate the maximum gallons of rain running off the roof in a single rain event from a home that measures 47 feet long and 27 feet wide at the drip line of the roof. It is not unusual for heavy storms in the example area to drop 2 inches of rain. To determine the runoff from such a rain event you will divide the 2 inches of rainfall by 12 inches of rainfall per foot to convert inches to feet for use in the equation. Since the roof is a rectangular area, use the following calculation for catchment area:

(length (ft) × width (ft)) × rainfall (ft) × 7.48 gal/ft^3 = maximum runoff (gal)
(47 ft × 27 ft) × (2 in ÷ 12 in/ft) × 7.48 gal/ft^3 = maximum runoff (gal)
1,269 ft^2 × 0.167 ft × 7.48 gal/ft^3 = 1,585 gal

1,585 gal = maximum runoff

Equation 4B.
Possible Volume of Runoff from a Roof or Other Impervious Catchment Area (metric units)

catchment area (m^2) × rainfall (mm^2) = maximum runoff (liters)

Calculations for annual rainfall, a rainy season, or an event would be similar to those for English units.

Equation 5A.
Estimated Net Runoff from a Catchment Surface Minus Potential Water Loss (English units)

catchment area (ft^2) × rainfall (ft) × 7.48 gal/ft × runoff coefficient = net runoff (gal)

Impervious catchment surfaces such as roofs or non-porous pavement can lose 5% to 20% of the rain falling on them due to evaporation, wind, overflow of gutters, leaks in downspouts, and minor infiltration into the catchment surface itself. The more porous or rough your roof surface, the more likely it will retain or absorb rainwater. On average, pitched metal roofs lose 5% of rainfall, allowing 95% to flow to the cistern. Concrete or asphalt roofs retain around 10%, while built-up tar and gravel roofs can retain 15% to 20%. (However, the percent of retention is a function of the size and intensity of the rain event so more porous roof surfaces could absorb up to 100% of small, light rain events.) To account for potential loss, determine the runoff coefficient that is appropriate for your area and impervious catchment surface (0.80 to 0.95).

EXAMPLE CALCULATING NET ANNUAL RUNOFF FROM A ROOF:

Calculate the net gallons of rain running off the roof in an average year from a home that measures 47 feet long and 27 feet wide at the drip line of the roof. Rainfall in this location averages 10.5 inches per year, so you will divide this by 12 inches of rainfall per foot to convert inches to feet for use in the equation. (Note: You can use the same equation to calculate the runoff from a single storm, by simply using the rainfall from that storm instead of annual average rainfall in the equation.) Assume that the loss of water that occurs on the catchment surface is at the high end of the range so you get a conservative estimate of net runoff. This means you select a runoff coefficient of 80%, or 0.80. You might want a conservative estimate if planning water needs for landscaping, but you might want an unmodified estimate if trying to size a cistern. Since the roof is a rectangular area, use the following calculation for catchment area, LENGTH × WIDTH as in Equation 1A:

$(\text{length (ft)} \times \text{width (ft)}) \times \text{rainfall (ft)} \times 7.48 \text{ gal/ft}^3 \times 0.80 = \text{net runoff (gal)}$
$(47 \text{ ft} \times 27 \text{ ft}) \times (10.5 \text{ in} \div 12 \text{ in/ft}) \times 7.48 \text{ gal/ft}^3 \times 0.80 = \text{net runoff (gal)}$
$1{,}269 \text{ ft}^2 \times 0.875 \text{ ft} \times 7.48 \text{ gal/ft}^3 \times 0.80 = 6{,}644 \text{ gal}$

6,644 gal = net runoff

Based on this, a realistic estimate of the volume of water that could be collected off the 47 foot by 27 foot example roof in an average year is 6,644 gallons.

RUNOFF COEFFICIENTS

The runoff coefficient is defined as a decimal fraction of water that runs off a surface onto which it falls. A runoff coefficient of 1.00 means that 100% of the water runs off the surface; a runoff coefficient of 0.00 means all rainwater will infiltrate into the soil (none runs off; this can happen with highly mulched and vegetated landscapes); 0.50 means that half the water falling on the surface will sink in, the other half running off.

The runoff coefficients on this page are rough estimates, for they are dependent on many factors, among them:

- Climate and season of the year (which will affect whether the ground is saturated or frozen, for instance, the type of precipitation, and the amount of vegetation that can be supported)
- Soil type (clayey soils allow less water to infiltrate and have higher runoff coefficients, while sandy porous soils will have low ones)
- Slope of the surface (runoff will be higher on a sloped surface versus a flat one)
- Vegetation: amount, type, and spacing (generally, more vegetation leads to more infiltration, and a lower runoff coefficient)
- Intensity of rainfall (a heavy or prolonged rain will produce greater runoff as the soil or its surface becomes saturated; a light rainfall may just cling to the soil surface or vegetation and evaporate)

The following runoff coefficients are for the southwestern U.S., though they give ballpark ranges for many situations:

- Impervious paving or a building's roof: range 0.85-0.95
- Healthy Sonoran Desert Uplands: range 0.20-0.70, average 0.30-0.50
- Bare earth: range 0.20-0.75, average 0.35-0.55
- Grass/lawn: range 0.05-0.35, average 0.10-0.25
- For gravel, use the coefficient of the ground below the gravel.

For additional runoff coefficients and information see the following urls:
www.emrl.byu.edu/gsda/data_tips/tip_soiltype_table.html, and
water.me.vccs.edu/courses/CIV246/table2.htm

EXAMPLE CALCULATING *ANNUAL* NET RUNOFF FROM A *BARE SECTION OF YARD*:

In an area receiving 18 inches of rain in an average year, you want to calculate the runoff from a 12 foot by 12 foot bare section of yard that drains to an adjoining infiltration basin. The soil is clayey and compacted, and you estimate its runoff coefficient to be 60% or 0.60.

catchment area (ft^2) × rainfall (ft) × 7.48 (gal/ft) × runoff coefficient = net runoff (gal)

12 ft × 12 ft × (18 in ÷ 12 in/ft) × 7.48 gal/ft^3 × 0.60 = net runoff gal
144 ft^2 × 1.5 ft × 7.48 gal/ft^3 × 0.60= 969 gal

969 gal = net runoff

Based on this, a realistic estimate of the volume of runoff that could be collected off the 12 foot by 12 foot section of bare earth within the adjoining infiltration basin is 969 gallons in an average year.

EXAMPLE CALCULATING RUNOFF FROM A SINGLE STORM EVENT ON ESTABLISHED LAWN (GRASS):

The runoff coefficient for this established lawn is assumed to be 20% or 0.20, and the maximum storm event is 3 inches:

12 ft × 12ft × (3 in ÷ 12 in/ft) × 7.48 gal/ft^3 × 0.20 = net runoff gal
144 ft^2 × 0.25 ft × 7.48 gal/ft^3 × 0.20 = 54 gal

54 gal = net runoff

Equation 5B.
Estimated Net Runoff from an Impervious Catchment Surface Minus Potential Water Loss (metric units)

catchment area (m^2) × rainfall (mm) × runoff coefficient = net runoff (liters)

EXAMPLE:

In an area receiving 304 millimeters of rain a year, you have a rooftop catchment surface that is 15 meters long and 9 meters wide, and you want to know how much rainfall can realistically be collected off that roof in an average year. You want a conservative estimate of annual net runoff, so you use a runoff coefficient of 80% or 0.80. (Since the roof is a rectangular area, use the following calculation for catchment area as in Equation 1B—CATCHMENT AREA m^2 = LENGTH m × WIDTH m—which is figured into the equation below.) Note: An explicit conversion to liters is not necessary in this equation because there are 1,000 mm/m and 1,000 liters/m^3.

(length (m) × width (m)) × rainfall (mm) × 0.80 = net runoff (liters)
(15 m × 9 m) × 304 mm × 0.80 = net runoff (liters)
135 m^2 × 304 mm × 0.80 = 32,832 liters

32,832 liters = net runoff

A realistic estimate of the volume of water that could be collected off this 15 meter by 9 meter roof in a year of average rainfall is 32,832 liters.

Equation 6A.
Berm 'n Basin (b'nb): Approximate Maximum Water-Holding Capacity or Volume (English units)

1/2 × width (ft) × depth (ft) × length (ft) = volume (ft^3)

- **Width** is the horizontal distance from the top of the lip of the berm's spillway to the point upslope where water will back up to.
- **Depth** is the vertical distance from the bottom of the basin to the top of the berm's spillway.
- **Length** is the distance that the b'nb runs along the land contour.

To calculate the maximum volume of water your berm 'n basins could hold at one time, you will need to know the depth, width, and length of your b'nb. Since the water will be held within a rounded triangular space rather than a rectangular space, you will use the equation for the area of a triangle, in this case: AREA = 1/2 × WIDTH × Maximum DEPTH, and therefore the VOLUME OF WATER-HOLDING CAPACITY (ft^3) = AREA × LENGTH. Then multiply the gallons by 7.48 gallons per cubic foot. So:

0.5 × width (ft) × depth (ft) × length (ft) × 7.48 gal/ft^3 = b'nb capacity (gal)

EXAMPLE BERM 'N BASIN:

You wish to capture runoff from a large sloping yard and are considering a b'nb. Calculate the approximate volume in gallons of a basin that's 10 feet wide, 2 feet maximum depth, and 40 feet long:

0.5 × 10 ft × 2 ft × 40 ft × 7.48 gal/ft^3 = b'nb capacity (gal)
400 ft^3 × 7.48 gal/ft^3 = 2,992 gal

Note that the calculations in equations 6A, 6B, 7A, and 7B do not take into account any water infiltrating into the soil, only water collected on the surface and runoff from upslope.

Equation 6B.
Berm 'n Basin: Approximate Maximum Water-Holding Capacity or Volume (metric units)

1/2 × width (m) × depth (m) × length (m) = volume (m^3)

Measure the width, depth, and length of the b'nb using the definitions provided in Equation 6B. Remember that every cubic meter contains 1,000 liters.

0.5 × width (m) × depth (m) × length (m) × 1,000 liters/m^3 = b'nb capacity (liters)

EXAMPLE:

A b'nb is 6 meters wide, 0.5 meters deep, and 15 meters long.

0.5 × 6 m × 0.5 m × 15 m × 1,000 liters/m^3 = b'nb capacity (liters)
15 m^3 × 1,000 liters/m^3 = 22,500 liters

Equation 7A.
Berm 'n Basin: Approximate Capacity in Cubic Feet per Foot of Length (English units)

$0.5 \times$ width (ft) $\times$ depth (ft) $\times$ length (1 ft) = b'nb capacity (ft^3/1 ft length of b'nb)

To calculate the water-holding capacity for each 1-foot length of the b'nb instead of for a specific length, you only need the capacity in cubic feet, not gallons. You will need this information to calculate b'nb *spacing* distance (Equation 8A):

EXAMPLE:

For the b'nb that's 10 feet wide and 2 feet maximum depth:

0.5×10 ft $\times$ 2 ft $\times$ 1 ft length = 10 ft^3/1 ft length

Note: To get gallons, multiply your cubic-feet result by 7.48 gal/ft3. In this case you get 74.8 gal/1 ft length of b'nb.

Equation 7B.
Berm 'n Basin: Approximate Capacity in Liters per Meter of Length (metric units)

$0.5 \times$ width (m) $\times$ depth (m) $\times$ length (1 m) $\times$ 1,000 liters/m^3 = b'nb capacity (liters/1 m length of b'nb)

This calculates the water-holding capacity for each 1 meter length of the b'nb instead of for a specific length.

EXAMPLE:

For the b'nb that is 6 meters wide and 0.5 meters maximum depth:

0.5×6 m $\times$ 0.5 m $\times$ 1 m $\times$ 1,000 = 1,500 liters/1 m length

You will need this information to calculate metric b'nb spacing distance (Equation 8B).

Equation 8A.
Berm 'n Basin Spacing Distance (English units)

(b'nb water holding capacity (ft^3/1 ft length)) $\div$ (runoff coefficient $\times$ rainfall from a large storm (ft)) = b'nb spacing distance (ft)

To figure out the spacing distance between b'nbs, i.e., the distance between one berm and the next berm above it, you will first need to calculate the per-foot holding capacity of your b'nb. You will also need to know the approximate typical percentage of total rainwater that will run off a slope, known as the *runoff coefficient*; see the information and sample runoff coefficients in Equation 5. Finally you will want to know the rainfall from a large storm.

EXAMPLES:

Now, we'll figure out how far apart to put several b'nbs. The example site has bare earth with clayey soils, so we'll use the high end of the average runoff coefficient for bare earth, 0.55. We want to harvest most of the rainfall runoff from a large storm—in Tucson, Arizona, this is a 2-inch rainfall event. We want rainfall to be expressed in units of feet instead of inches, with 2 inches divided by 12 inches/foot = 0.17 feet of rainfall.

Then, we use the water-holding capacity of the b'nb calculated in Equation 7A, expressed in units of cubic feet of volume *per 1 linear foot* of berm 'n basin (the result in Equation 7A was 10 ft^3 per foot of length).

(10 ft^3 /1 ft length of b'nb) ÷ (0.55 × 0.17 ft) = 107 ft spacing

This means if you construct your b'nbs about 100 feet apart on the landscape, you will capture most of the rainfall runoff from a large storm in Tucson, Arizona, most of the time.

To capture all of the water from larger rainfalls in Tucson, we use the highest runoff coefficient for bare dirt, 0.75, and use a rainfall of 3 inches, or 0.25 feet (the chance of a 3-inch rain storm happening in any given year in Tucson is 1 in 100) and calculate spacing distance:

(10 ft^3 /1 ft length of b'nb) ÷ (0.75 × 0.25 ft) = 53 ft spacing

So b'nbs spaced about 50 feet apart in Tucson would catch every drop of runoff water in a rain event not exceeding 3 inches of precipitation. Remember b'nbs *collect silt and detritus over time*, plus they lose some volume when mulch is thick, so always err on the side of making b'nbs closer together and larger.

Equation 8B.
Berm 'n Basin Spacing Distance (metric units)

b'nb water-holding capacity (liters/1 m length) ÷ (runoff coefficient × rainfall from a large storm (mm)) = b'nb spacing distance (m)

See Equation 8A for more information. Again you will use the runoff coefficients found in Equation 5 and the result from the b'nb capacity per meter length (Equation 7B). Note: An explicit conversion to liters is not necessary in this equation because there are 1,000 mm/m and 1,000 liters/m^3

EXAMPLE:

Using 1,500 liters per meter length (Equation 7B), and assuming a runoff coefficient of 0.30 from established grass growing in poor soil, you want to catch every drop from a maximum 50-mm storm:

(1,500 liters per 1 m length) ÷ (0.30 × 50 mm) = 100 m

So the b'nb spacing distance in this case is 100 meters or less.

Equation 9A.
Terraces: Approximate Water-Holding Capacity or Volume (English units)

width (ft) × depth (ft) × length (ft) = volume of water-holding capacity (ft^3)

The calculation process for terraces is generally the same as that used for berm 'n basins. The one difference, because a terrace is flat, is that the terrace calculation is adjusted to reflect the more rectangular shape (in cross-section) of the terrace.

- **Width** is the distance from the inside of the outer berm of the terrace to the slope into which the terrace is cut and where water will back up to.
- **Depth** is the vertical distance from the bottom of the terrace's basin to the top of its overflow spillway.
- **Length** is the distance that the terrace runs along the land contour.

EXAMPLE:

You're planning to build a terrace that's 8 feet wide, 4 inches or 1/3 (0.33) foot in depth below the spillway, and 24 feet long, and want to determine its capacity in square feet or gallons to know what vegetation it could support without supplemental watering.

$8 \text{ ft} \times 1/3 \text{ ft} \times 24 \text{ ft} = 64 \text{ ft}^3$

To get gallons, just multiply your cubic-feet result by 7.48 gal/ft^3.

$64 \text{ ft}^3 \times 7.48 \text{ gal/ft}^3 = 479 \text{ gallons}$

So this terrace can hold about 480 gallons. Remember that this amount does not include water infiltrating into the soil, etc. See appendix 4 for calculating water needs of plants.

Equation 9B.
Terraces: Approximate Water-Holding Capacity or Volume (metric units)

width (m) × depth (m) × length (m) × 1,000 (liters/m^3) = volume of water-holding capacity (liters)

See Equation 9A for information on width, depth, and length measurements.

Equation 10A.
Terrace Capacity per Foot of Length (English units)

width (ft) × depth (ft) × length (1 ft) = terrace capacity (ft^3/1 ft length of terrace)

This calculates the per-unit volume of your terrace. In some cases, you may not need this calculation, as the constraints of a small back yard may determine the size of your terrace. However, in terracing a larger area with catchment area upslope, it will be useful for calculating spacing between terraces in Equation 11.

EXAMPLE: ENGLISH UNITS

To get cubic feet per 1 foot of terrace length, using the example of a terrace that's 24 foot wide and 4 inches or 1/3 foot deep:

$24 \text{ ft} \times 1/3 \text{ ft} \times 1 \text{ ft} = 8 \text{ ft}^3$ per 1 foot of terrace length

Equation 10B.
Terrace Capacity per Meter of Length (metric units)

width (m) × depth (m) × length (1 m) × 1,000 liters/m^3 = terrace capacity (liters/1 m length of terrace)

EXAMPLE: METRIC UNITS

This terrace is 7 meters wide, and 10 centimeters (0.10 meters) deep. Note that you need to multiply by 1,000 liters/m^3 to get a result in liters.

7 m × 0.10 m × 1 m × 1,000 liters/m^3 = 700 liters per 1 meter of terrace length

Equation 11A. Terrace Spacing Distance (English units)

Use the same equation as 8A, substituting "terrace" for b'nb

Equation 11B. Terrace Spacing Distance (metric units)

Use the same equation as 8B, substituting "terrace" for b'nb

Equation 12: Optimum Terrace Width

maximum depth of cut in the soil ÷ the degree of the slope = width of terrace

In dryland areas, you can calculate the optimum width of a terrace with this calculation from Herman J. Finkel's *Semiarid Soil and Water Conservation*. Note that "maximum depth of cut" refers to the depth of soil, which can be shallow on steep slopes.

EXAMPLE: ENGLISH UNITS

On a 10% or 0.10 slope, if the maximum allowable cut is 1.5 feet, calculate as follows:

1.5 ft ÷ 0.10 = 15 ft

The width of the terrace would be 15 feet.

EXAMPLE: METRIC UNITS

For metric the calculation is similar.

0.5 m ÷ 0.10 = 5 meters

Equation 13. Circular Infiltration Basin Capacity or Volume

$\pi \times \text{depth} \times ((R_1 \times R_2) + R_1^2 + R_2^2) \div 3 = \text{basin capacity}$

The measurements taken as follows:

- **Depth** is the distance from the bottom of the basin to the top of its rim (or the lip of the spillway if you have one).
- **Diameters (circular basin)**. Because the edges of the basin are sloped, two different diameter measurements are used: one (D_1) measured at the bottom of the basin, and the second (D_2) measured at the top of the basin. Diameter is easier to measure than radius, but the radius of each circle is 1/2 its diameter: Hence R_1 and R_2 are each half of D_1 and D_2, respectively.

Keep in mind that because it's so difficult to measure large basins accurately, all your calculations will in any case give approximate volumes. In the calculations below, all numbers, including π, have been rounded off to two decimal places, and the results have been rounded off to whole numbers. Note: the one-third factor (the number 3) in the equation is a geometric constant associated with conical volumes.

Use the same unit of measurement for all measurements, for instance, all English measurements should be in feet, all metric measurements in meters or in centimeters.

EXAMPLE (ENGLISH UNITS):

For a circular basin with a depth of 2 feet, bottom radius of 6.5 feet, and top radius of 12.5 feet, the calculation is as follows:

$\pi \times 2\text{ ft} \times ((6.5\text{ ft} \times 12.5\text{ ft}) + (6.5\text{ ft})^2 + (12.5\text{ ft})^2) \div 3 = \text{Basin capacity (ft}^3)$
$\pi \times 2\text{ ft} \times (81.25\text{ ft}^2 + 42.25\text{ ft}^2 + 156.25\text{ ft}^2) \div 3 = \text{Basin capacity (ft}^3)$
$3.14 \times 2\text{ ft} \times 279.75\text{ ft}^2 \div 3 = \text{Basin capacity (ft}^3)$
Basin capacity = 586 ft^3

Then, to convert cubic feet to gallons:
Multiply 586 ft^3 by 7.48 gallons/ft^3 to convert to 4,383 gallons of basin capacity.

If your basin calculation uses meters, multiply the result of cubic meters (m^3) by 1,000 liters/m^3 to convert to liters.

OTHER APPLICATIONS OF THESE INFILTRATION BASIN CALCULATIONS:

The circular and rectangular basin volume calculations can also be used in reverse, i.e., for calculating the volume of soil removed from an excavation, or estimating the volume of soil needed to fill a planter, as below:

EXAMPLE:

You want to know the capacity or volume of a circular planter that measures 2 feet in diameter at its base, 3 feet at its top rim, and is 2 feet tall. The bottom and top radii (R = half the diameter D) are 1 and 1.5, respectively.

$\pi \times \text{depth} \times ((R_1 \times R_2) + R_1^2 + R_2^2) \div 3 = \text{capacity}$
$\pi \times 2\text{ ft} \times ((1\text{ ft} \times 1.5\text{ ft}) + 1\text{ ft}^2 + 2.25\text{ ft}^2) \div 3 = \text{capacity}$
$3.14 \times 2\text{ ft} \times 4.75\text{ ft}^2 \div 3 = \text{capacity}$

Capacity = 9.94 ft^3

Just a bit over 1/3 cubic yard, or multiplying by 7.48 gals/ft^3, you get about 74 gallons.

Equation 14. Square or Rectangular Basin Capacity or Volume

$$(\text{depth} \times ((L_1 \times W_1) + (L_2 \times W_2) + (\text{sqrt}\ (L_1 \times W_1 \times L_2 \times W_2))) \div 3 = \text{basin capacity}$$

with the sqrt being the square root, which is a function found on most calculators. Note: the one-third factor (the number 3) in the equation is a geometric constant associated with pyramid volumes.

The measurements for the rectangular basin calculation:

- **Depth** is the distance from the bottom of the basin to the top of its rim (or the lip of the spillway if you have one).
- **Widths (rectangular basin)**. Because the edges of the basin are sloped, two different width measurements are used: one measured at the bottom of the basin (W_1), and the second measured at the top of the basin (W_2).
- **Lengths (rectangular basin)**. Because the edges of the basin are sloped, two different length measurements are used: one measured at the bottom of the basin (L_1), and the second measured at the top of the basin (L_2).

Use the same unit of measurement for all measurement. For example, all English measurement should be in feet.

EXAMPLE:

Using the example basin (with a depth of 1.5 feet, bottom length of 16.5 feet, bottom width of 14 feet, top length of 20 feet, and top width of 17 feet), the calculation is as follows:

$(1.5\ \text{ft} \times ((16.5\ \text{ft} \times 14\ \text{ft}) + (20\ \text{ft} \times 17\ \text{ft}) + (\text{sqrt}\ \{16.5\ \text{ft} \times 14\ \text{ft} \times 20\ \text{ft} \times 17\ \text{ft}\}))) \div 3 = \text{basin capacity}\ (\text{ft}^3)$
$(1.5\ \text{ft} \times ((16.5\ \text{ft} \times 14\ \text{ft}) + (20\ \text{ft} \times 17\ \text{ft}) + (\text{sqrt}\ \{78{,}540\ \text{ft}^4\}))) \div 3 = \text{basin capacity}\ (\text{ft}^3)$
$(1.5\ \text{ft} \times ((16.5\ \text{ft} \times 14\ \text{ft}) + (20\ \text{ft} \times 17\ \text{ft}) + (280.25\ \text{ft}^2))) \div 3 = \text{basin capacity}\ (\text{ft}^3)$
$(1.5\ \text{ft} \times (231\ \text{ft}^2 + 340\ \text{ft}^2 + 280.25\text{ft}^2)) \div 3 = \text{basin capacity}\ (\text{ft}^3)$
$(1.5\ \text{ft} \times 851.25\ \text{ft}^2) \div 3 = \text{basin capacity}\ (\text{ft}^3)$
$1{,}267.86\ \text{ft}^3 \div 3 = \text{basin capacity}\ (\text{ft}^3)$
basin capacity = 426 ft^3

Then, to convert cubic feet to gallons:
Multiply 426 ft^3 by 7.48 gallons/cubic foot to convert to 3,186 gallons of basin capacity.

If you used meters and your result was in cubic meters, multiply by 1,000 liters/m^3 to convert to liters.

Equation 15. Engineering Calculation for Diversion Swale Sizing

There are two steps needed to calculate an adequate size for the diversion swale. The *first step* is to estimate the maximum water flow into the swale. The second step is to estimate what dimensions the swale will need to handle this design inflow.

For the first step, we will use what engineers refer to as the Rational Method to estimate peak water flow. Note that the Rational Method is best used as a simple formula for small properties, and is not considered applicable for large catchments (i.e. over 300 acres or 121 ha). For large catchments the Soil Conservation Service "Curve Number" approach is recommended, for which references are widely available.

The basic formula of the Rational Method is:

$Q = CiA$

where Q = peak flow (cubic feet per second)
C = runoff coefficient for the catchment
i = rainfall intensity (inches per hour)
A= catchment area (acres)

The runoff coefficient is dimensionless, theoretically varying between 0 and 1. The runoff coefficient is smaller for catchments that have high infiltration and higher for those with low infiltration. Typical runoff coefficients are: paved areas 0.9; residential lots 0.3-0.7 (dependent on amount of impervious area, type of soil and amount of vegetation); unmodified ground 0.2-0.6 (dependent on type of soil and amount of vegetation).

The rainfall intensity the swale is designed for can vary, but we suggest using a 100-year rainfall event recurrence interval. A 100-year rainfall event is defined as a rainfall of a given duration of time that can be expected to occur in the area once in a 100-year period. To estimate peak flow, rainfall duration should match the time of concentration for the catchment. The time of concentration for the catchment is defined as the length of time after rain begins that all portions of the catchment contribute to catchment outflow. The minimum time of concentration to use is 5 minutes, which would apply to most residential properties. Larger scale applications will have larger times of concentration, which can be either estimated with personal judgment, observed directly on site during a storm, or found using the formula below.

$T_c = 0.0078\ L^{0.77}\ S^{-0.385}$

where T_c is time of concentration (minutes)
L is length of channel through the catchment from boundary to outflow (feet)
S is slope (ft/ft)

After the time of concentration is obtained, visit http://dipper.nws.noaa.gov/hdsc/pfds/ to find rainfall depth. This government-data website allows you to focus on different regions of the U.S., and then pull up a table of rainfall depths for different rainfall durations (such as 5 minutes) and different recurrence intervals (such as 100 years). With the rainfall depth we can calculate rainfall intensity:

i (inches per hour) = 60 $\times$ rainfall depth (inches) $\div$ T_c (minutes)

Catchment area in acres should be straightforward to measure. To convert square feet to acres, divide by 43,560. Now we have all variables necessary to calculate peak flow.

Peak Flow Example Calculation:
Consider a typical Tucson, Arizona property about 0.2 acre in size.

The runoff coefficient is estimated at 0.4.

We estimate the time of concentration to be 5 minutes.

For a weather site listed in Tucson using the map found at http://dipper.nws.noaa.gov/hdsc/pfds/, the rainfall depth associated with a 5-minute storm of 100-year recurrence is 0.77 inches. The rainfall intensity is 9.24 inches per hour.

The peak flow (q) associated with design conditions is 0.75 (rounded up) cubic feet per second.

After estimating the peak flow, the *second step* is to size the diversion swale to handle the peak flow. For this we will use the Manning equation to estimate average velocity of flow in a given-dimensioned swale and see if this is adequate to pass the design flow. Through iteration, minimum dimensions of the swale can be estimated. The Manning equation is:

$$V = (1.49\ R^{2/3}\ S^{1/2}) \div n$$

where V = velocity (feet per second)
R = hydraulic radius (feet)
S = slope (ft/ft), here slope is vertical fall divided by horizontal distance
n = Manning's roughness factor

Hydraulic radius is the linear distance across the most limiting (smallest) swale cross-section, measured along the earth from the swale edge down to the bottom, across the swale floor, and up to the facing swale edge. A typical Manning's roughness factor for an earth swale is 0.05. A very clean swale might be as low as 0.03, and a very obstructed (i.e. with check dams) swale might carry a roughness as high as 0.1. After velocity has been estimated with the Manning equation, the volume capacity of the swale can be found by multiplying velocity by the most limiting cross-sectional area of the swale.

SWALE VOLUME CAPACITY CALCULATION EXAMPLE:

Continuing the example of a typical Tucson property begun above, suppose we are planning to excavate a diversion swale with hydraulic radius of 2 feet, a slope of 1/100, and a cross-sectional area of 0.3 square feet. Let's use a typical Manning's roughness value of 0.05. Velocity and volume are then:

$$V = 1.49 \times 2^{2/3} \times 0.01^{1/2} \div 0.05$$
$$= 4.73 \text{ feet per second}$$

$$Q = V \times A$$
$$= 4.73 \times 0.3$$
$$= 1.41 \text{ cubic feet per second}$$

The 1.41 surpasses the 0.75 result as found in step one using the Rational Method, so we're good to go. The designed swale would still have capacity beyond the 100-year rainfall event associated with the time of concentration for the catchment. While the swale could be sized smaller and still handle the 0.75 cubic feet per second design flow, the margin might come in handy as swales tend to fill in over time (reducing the cross-section) or as any vegetation in the swale matures (increasing the Manning's roughness factor).

REFERENCES:

David R. Maidment, ed., Handbook of Hydrology, McGraw-Hill Inc, 1992.

http://dipper.nws.noaa.gov/hdsc/pfds/ Accessed 6/7/07