Appendix 2

Water-Harvesting Earthworks Calculations

Box numbers (with their examples, illustrations, and explanations) and figures referenced in this appendix can be found in the book *Rainwater Harvesting for Drylands and Beyond, Volume 2, 2nd Edition*

List of Equations and Other Information

Box A2.1. 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 cubic yard = 27 cubic feet
1 ton = 2000 pounds
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 $\pi = 3.14$ *

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

CONVERSIONS FOR METRIC UNITS
To convert cubic centimeters to liters, divide cubic centimeters by 1,000
To convert kilograms to metric ton, divide by 1,000
1 metric ton = 1000 kg

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 look only 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 needs only 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 A2.2. 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 A2.3. Meteorological and Climate Resources

ONLINE RESOURCES

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

Arizona Meteorological Network. **https://cals.arizona.edu/AZMET/** 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

See the One-Page Place Assessments page at HarvestingRainwater.com for a distilled page of great info on sun, climate, wind, water, watergy, watersheds, totem species, and more for many locations around the globe—and how to create your own.

The U.S. National Forest Service for remote weather stations, though the data is not as comprehensive or as standard.

Local airports.

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 volume of rain, in gallons, 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 volume of rain, in gallons, 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

For another example, illustration, and more explanation see box 1.3

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

catchment area (m^2) × rainfall (mm) = 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 volume of rain, in gallons, 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:

(length (ft) × width (ft)) × rainfall (ft) × 7.48 gal/ft^3 × 0.80 = net runoff (gal)
(47 ft × 27 ft) × (10.5 in ÷ 12 in/ft) × 7.48 gal/ft^3 × 0.80 = net runoff (gal)
1,269 ft^2 × 0.875 ft × 7.48 gal/ft^3 × 0.80 = 6,644 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 coefficient 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 surface below the gravel.

For additional runoff coefficients and information see
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

For another example, illustration, and more explanation see box 1.4 and fig. 1.22

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.

For another example, illustration, and more explanation see box 1.4 and fig. 1.22

Equation 6.

Circular or Oval Infiltration Basin Water-Holding Volume or Capacity, and Volume of Soil Excavated from Basin

$\pi \times R^2 \times \text{depth} = \text{volume}$

- $\pi = 3.14$
- **R**, **Radius** is half the diameter. **Diameter** is the distance from one side of a circular basin to the other, measured across the middle of the basin. To get an approximate average diameter of a basin with sloping or terraced banks, measure this distance about halfway down the depth of the basin. If the basin is an oval shape, measure the short diameter and the long diameter, add them up, and divide by two to get the average diameter.
- **Depth** is the distance from the top of a basin's rim, or the top of the lip of the overflow spillway if you have one, to the bottom of the basin.

This calculation will give you a conservative estimate of the basin's water-surge capacity since it does not take into account any of the water that will rapidly infiltrate into a well-constructed basin's soil and vegetation during the water surge.

Using this information also gives you a conservative estimate of the expanded or *swelled* volume of excavated soil you will have, since loose, excavated soil has more air incorporated into it than unexcavated soil. The average *swell factor* of excavated soil is 30% (more if clay, less if sand). This is important information if you need to estimate the volume of soil you need to transport somewhere else.

Use the same units for all measurements.

For instance, all English measurements should be in feet. The resulting English-unit basin capacity/volume will be in cubic feet, which you can convert to gallons by multiplying cubic feet by 7.48 gallons/cubic foot.

Metric measurements should be in meters. The resulting metric-unit basin capacity/volume will be in cubic meters, which you can convert to liters by multiplying cubic meters by 1000 liters/cubic meter.

EXAMPLE (ENGLISH UNITS):

To calculate the approximate gallons of water that a 1.5-foot deep oval basin with a relatively level bottom and sloping or terraced banks can hold, start by measuring the long and short oval diameters about halfway down the depth of the basin. In this example, you find that the longest diameter of the basin is 8 feet, and the shortest diameter of the basin is 5 feet.

To get the average diameter, add the two diameters together, then divide the sum by two ($8 + 5 = 13$, $13 \div 2 = 6.5$ feet, average diameter). To get the average radius, divide by two again ($6.5 \div 2 = 3.25$ feet, average radius).

$3.14 \times (3.25 \text{ ft})^2 \times 1.5 \text{ ft} = 49.74 \text{ ft}^3$ capacity of the basin, and the volume of excavated soil (without the swell factor).

To convert cubic feet to gallons, multiply by 7.48 gal/ft^3

$49.74\ ft^3 \times 7.48\ gal/ft^3 = 372$ gallons

See Equation 8 to estimate the basin's average annual capacity, and Equation 9 to estimate the basin's ballpark dollar per gallon (or liter) cost.

To account for the swell factor of excavated soil, multiply the soil volume by 30% (or 0.30) then add that to the total volume:

$49.74\ ft^3 \times 0.30 = 14.9\ ft^3$. So, $49.74\ ft^3 + 4.47\ ft^3 = 54.21\ ft^3$ of excavated soil (with the swell factor).

Trucking and landscape material companies typically measure materials in cubic yards. To convert cubic feet to cubic yards, divide the volume in cubic foot by $27\ ft^3/\ yd^3$. So, $54.21\ ft^3 \div 27\ ft^3/\ yd^3 = 2\ yd^3$ of excavated soil (with the swell factor)

For another example, illustration, and more explanation see box 2.2

Equation 7.
Square of Rectangular Infiltration Basin Water-Holding Volume or Capacity, and Volume of Soil Excavated from Basin

length × width × depth = volume

- **Length** is the longer of the two horizontal dimensions of a rectangular basin. To get an approximate average length of a basin with sloped or terraced banks, measure the length about halfway down the depth of the basin.
- **Width** is the shorter of the two horizontal dimensions of a rectangular basin. To get an approximate average width of a basin with sloped or terraced banks, measure the width about halfway down the depth of the basin.
- **Depth** is the distance from the top of a basin's rim, or the top of the lip of the overflow spillway if you have one, to the bottom of the basin.

This calculation will give you a conservative estimate of the basin's water-surge capacity since it does not take into account any of the water that will rapidly infiltrate into a well-constructed basin's soil and vegetation during the water surge.

Using this information also gives you a conservative estimate of the expanded volume of excavated soil you will have, since loose, excavated soil has more air incorporated into it than unexcavated soil. The average *swell factor* of excavated soil is 30% (more if clay, less if sand). This is important information if you need to estimate the volume of soil you need to transport somewhere else.

Use the same units for all measurements.

For instance, all English measurements should be in feet. The resulting English-unit basin capacity/volume will be in cubic feet, which you can convert to gallons by multiplying cubic feet by 7.48 gallons/cubic foot.

Metric measurements should be in meters. The resulting metric-unit basin capacity/volume will be in cubic meters, which you can convert to liters by multiplying cubic meters by 1000 liters/cubic meter.

EXAMPLE (ENGLISH UNITS):

To calculate the approximate volume of water in gallons that a 2-foot deep rectangular basin with a relatively level bottom and sloping or terraced banks can hold, measure the length and width. In this example, you find that the length is 11 feet and the width is 7 feet, as measured about halfway down the depth of the basin.

11 ft × 7 ft × 2 ft = 154 ft^3 capacity of the basin, and the volume of excavated soil (without the swell factor)

To convert to gallons multiply by 7.48 gal/ft^3
154 ft^3 × 7.48 gal/ft^3 = 1,151 gallons

See Equation 8 to estimate the basin's average annual capacity, and Equation 9 to estimate the basin's ballpark dollar per gallon cost.

To account for the swell factor of excavated soil, multiply the soil volume by 30% (or 0.30) then add that to the total volume:
154 ft^3 × 0.30 = 46.2 ft^3. So, 154 ft^3 + 46.2 ft^3 = 200.2 ft^3 of soil excavated
Trucking and landscape material companies typically measure materials in cubic yards. To convert cubic feet to cubic yards, divide the volume in cubic foot by 27 ft^3/ yd^3. So, 200.2 ft^3 ÷ 27 ft^3/ yd^3 = 7.4 yards3 of excavated soil (with the swell factor).

For another example, illustration, and more explanation see box 2.2

Equation 8.
Estimate Infiltration Basin's Minimum Annual Water-Harvesting Volume or Capacity

basin capacity × number of good rainfalls/year = minimum annual water-harvesting capacity of the basin

This calculation assumes that during each good rainfall in a year's time, the basin is filled to the top with water from a combination of direct rainfall and water runon flowing into the basin from adjacent areas. This calculation provides a conservative minimum estimate of the average annual water-harvesting capacity of the basin. It is conservative because it does not take into account the water that will rapidly infiltrate into a well-constructed basin during a good rainfall, allowing even more water runon to be harvested in that basin during the same rainfall. For purposes of this estimate, a good rainfall is assumed to be one inch of rain in English units, or 25 millimeters in metric units.

Use the same units for all measurements.
English measurements should be in gallons.
Metric measurements should be in liters.

EXAMPLE (ENGLISH UNITS):

To approximate the minimum average volume of water that a basin could capture in a year, use the example 372-gallon basin from Equation 6, and assume an average annual rainfall of 12 inches, arriving in a series of 12 good-sized rainfalls over the year. A *good-sized rainfall* in this context generates enough runoff to fill the basin. This is determined by the volume of rainfall, and the size and quality of the catchment surface directing its runoff to the basin (Equations 4 and 5). A 1-inch (25-mm) storm is typically sufficient, but even a 0.5-inch (12.5-mm) storm may be enough depending on your catchment and the intensity of the rain.

Divide 12 inches/year of rainfall by 1-inch/rainfall = 12 good water-harvesting rainfalls/year.

372 gallons × 12 good rainfalls/year = minimum of 4,464 gallons/year of basin water-harvesting capacity

EXAMPLE (METRIC UNITS)

To approximate the minimum average volume of water that a basin could capture in a year, use an example 1500-liter basin and assume an average annual rainfall of 300 millimeters, arriving in a series of 12 good-sized rainfalls over the year. A *good-sized rainfall* in this context generates enough runoff to fill the basin. This is determined by the volume of rainfall, and the size and quality of the catchment surface directing its runoff to the basin (Equations 4 and 5). A 25-mm rain is typically sufficient, but even a 12.5-mm rain may be enough depending on your catchment and the intensity of the rain.

Divide 300 millimeters/year of rainfall by 25-millimeters/rainfall = 12 good water-harvesting rainfalls/year.

1500 liters × 12 good rainfalls/year = minimum of 18,000 liters/year of basin water-harvesting capacity

Equation 9.
Estimate of Cost to Build Infiltration Basin per Annual Water-Holding Volume or Capacity

cost to construct basin ÷ minimum annual water-harvesting capacity of the basin = cost per volume of stored water

To estimate the construction cost per unit of a basin storage capacity over a year's time, first add up the total cost to construct the basin including labor, curb cuts, mulch, permits, dirt removal, rock to stabilize banks, and any other associated costs. Next, divide that by the minimum annual water-harvesting capacity of the basin to get the cost per unit of water-harvested capacity. The resulting cost just reflects the first year of basin use. Basins keep harvesting water for many years, so the cost per unit of stored water keeps going down every year.

Note that a basin or other earthwork infiltrating all its surface water within 12 hours or less has a much higher water-harvesting and flood-controlling capacity than an equal-sized tank, which can remain full or fullish for weeks or months after a good rain depending on how quickly and often the users open the tap and use the water.

EXAMPLE (ENGLISH UNITS):

To estimate the construction cost per unit of basin storage capacity over a year's time in English units, use the example basin from Equation 8 that has a minimum of 4,464 gallons/year of basin water-harvesting capacity, and assume a total cost to construct the basin was $800.

$800 ÷ 4,464 gallons/year = $0.18/gallon to build the basin in the first year of use—and this cost keeps going down year after year

EXAMPLE (METRIC UNITS):

To estimate the construction cost per unit of basin storage capacity over a year's time in metric units, use the example basin from Equation 8 above that has a minimum 18,000 liters/year of basin water-harvesting capacity, and assuming a total cost to construct the basin was $800.

$800 ÷ 18,000 liters/year = $0.04/liter to build the basin in the first year of use—and this cost keeps going down year after year

Equation 10A.
Berm 'n Basin (b'nb): Approximate Maximum Water-Holding Capacity or Volume (English units)

$1/2 \times$ width (ft) $\times$ depth (ft) $\times$ length (ft) = volume (ft^3)

For example, illustration, and more explanation see box 3.2

Equation 10B.
Berm 'n Basin: Approximate Maximum Water-Holding Capacity or Volume (metric units)

$1/2 \times$ width (m) $\times$ depth (m) $\times$ length (m) = volume (m^3)

Measure the width, depth, and length of the b'nb using the definitions provided in box 3.2. Remember that every cubic meter contains 1,000 liters.

$0.5 \times$ width (m) $\times$ depth (m) $\times$ length (m) $\times$ 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 $\times$ 0.5 m $\times$ 15 m $\times$ 1,000 liters/m^3 = b'nb capacity (liters)
15 m^3 $\times$ 1,000 liters/m^3 = 22,500 liters

Equation 11A.
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)

For an example, illustrations, and more explanation see box 3.2

Equation 11B.
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 12B).

Equation 12A.
Berm 'n Basin Spacing Distance (English units)

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

For an example, illustrations, and more explanation see box 3.3

Equation 12B.
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 box 3.3 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 11B). 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 11B), 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 13A.
Terraces: Approximate Water-Holding Capacity or Volume (English units)

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

For an example, illustrations, and more explanation see box 4.1

Equation 13B.
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 box 4.1 for information on width, depth, and length measurements.

Equation 14A.
Terrace Capacity per Foot of Length (English units)

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

For an example, illustrations, and more explanation see box 4.1

Equation 14B.
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 15A. Terrace Spacing Distance (English units)

Use the same equation as 12A, substituting "terrace" for b'nb

Equation 15B. Terrace Spacing Distance (metric units)

Use the same equation as 12B, substituting "terrace" for b'nb

Equation 16: Optimum Terrace Width

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

Note that "maximum depth of cut" refers to the depth of soil, which can be shallow on steep slopes.

For an example, illustrations, and more explanation see box 4.2

Equation 17. 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 have to handle this 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, search on-line for NOAA's Precipitation Frequency Data Server (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 × rainfall depth (inches) ÷ 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 acres 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 on-line at NOAA's Precipitation Frequency Data Server (PFDS) webpage, 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:

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

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

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.

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Equation 18.
Estimating Rock Volume and Tonnage for Ordering Materials

Your supplier may charge by the English ton (metric ton), or by the cubic yard (cubic meter) for rock—though charging by weight is generally more accurate. See below for how to calculate both. (Thanks to Steve Carson of Rangeland Hands, Inc. for these calculations.)

Note that when building an in-channel structure such as a one-rock dam, the 'width' refers to the width of the channel the structure is built in. In the example below, this width is equal to 10 feet (3 meters). The length of the structure is the distance the structure covers from upstream to downstream. In the example below, the length is 5 feet (1.5 *meters). This way of referring to width and length is different than that used in traditional geometry, where width is the shorter dimension and length is the longer dimension.*

EXAMPLE (ENGLISH UNITS):

Step 1: Calculate area of rock structure:

width (ft) × length (ft) = area (ft^2)
Example: A one-rock dam is 10 feet in width and 5 feet in length. To determine its volume in square feet:
10 ft × 5 ft = 50 ft^2 rock structure area

Step 2: Calculate rock structure volume based on rock size:
The standard rock size used in hand-built structures is 6- to 12-inch rock, which represents a rough range of the dimensions of the rock. A mix of 6- to 12-inch rock will have an average dimension of 9 inches [(6 in + 12 in) ÷ 2 = 9 in]. Converted to feet, this equals 0.75 feet (9 in ÷12 in/ft = 0.75 ft). This is the height of your one-rock dam structure in feet. This is multiplied by area to calculate the rock structure volume.

area (ft^2) × height (ft) = volume (ft^3)
Example: The one-rock dam is 10 feet in width, 5 feet in length, and 0.75 feet in height. To determine its volume:
10 ft × 5 ft × 0.75 ft = 37.5 ft^3 rock structure volume

Step 3: Convert cubic feet to cubic yards:
Rock might be ordered by the cubic yard. A cubic yard equals 27 cubic feet. To convert cubic yards to cubic feet, divide by 27.

Example: A one-rock dam has a volume of 37.5 ft^3. To determine its volume in cubic yards:
37.5 ft^3 ÷ 27 ft^3/yd^3 = 1.38 yd^3 rock structure volume

Step 4: Convert cubic yards to tons:
Sometimes, rock is bought by the ton. A ton of rock = 1.5 × cubic yards of rock.

Example: A one-rock dam has a volume of 1.38 yd^3. To determine its weight in tons:
1.38 yd^3 × 1.5 = 2.08 tons of rock needed to build a 10-ft wide, 5-ft long, 0.75-ft high one-rock dam

EXAMPLE (METRIC UNITS):

Step 1: Calculate area of rock structure:

width (m) × length (m) = area (m^2)
Example: A one-rock dam is 3 meters in width and 1.5 meters in length; to determine its volume in square feet:
3 m × 1.5 m = 4.5 m^2 rock structure area

Step 2: Calculate rock structure volume based on rock size:
The standard rock size used in hand-built structures is 15- to 30-centimeter rock, which represents a rough range of the dimensions of the rock. A mix of 15- to 30-cm rock will have an average dimension of 22.5 centimeters [(15 cm + 30 cm) ÷ 2 = 22.5 cm]. Converted to meters, this equals 0.225 m (22.5 cm ÷ 100 = 0.225 m). This is the height of your structure in meters. This is multiplied by area to calculate the rock structure volume.

area $m^2 \times$ height (m) = volume (m^3)

Example: The one-rock dam is 3 meters in width, 1.5 meters in length, and 0.225 meters in height; to determine its volume:

3 m $\times$ 1.5 m $\times$ 0.225 m =1 m^3 rock structure volume

Step 3: Convert cubic meters to metric tons:

Sometimes, rock is bought by the metric ton. A cubic meter of rock weighs around 1600 – 1800 kilograms. To convert this to metric tons, divide kilograms by 1000 kilograms per metric ton.

weight (kg) ÷ 1000 kg/metric ton = metric tons

Example: A one-rock dam has a volume of 1 m^3. To determine its weight in tons:

1700 kg ÷ 1000 kg/metric ton = 1.7 metric tons of rock needed to build a 3 meter wide, 1.5 meters long, and 0.225 meter high one-rock dam

ON-LINE VOLUME CALCULATORS AND MORE

For a website that may have some useful calculators for you see https://www.aqua-calc.com/page/volume-calculators