# Planning and design of micro-catchment systems

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## 1. Planning and Design

The following are 8 simplified steps for designing a functional micro-catchment water harvesting system for agriculture

**Step 1: determine the need and potential for a water harvesting system**

Water harvesting system is needed where no other source is available or when it is a cheaper alternative. In remote areas where no tap water is available there is a great need for a water harvesting system to provide households with water for drinking and sanitation. In many places, the cost of rainwater harvesting is lower than buying water when needed. For agriculture, which is the subject of this manual the shortage of irrigation water resources or the scarcity of rainwater that is unable to support economic agriculture is a good reason to have a water harvesting system.

Generally, one needs to determine the need for water harvesting in association with the crop to be grown. The crop, the local environment (climate, soil, topography, etc.) and the need for water harvesting are all linked together. Climate and soil should be suitable for the crop selected. For example, one cannot grow trees in shallow soils or frost sensitive crop in an area with frequent frost. It is advisable to select crops that are already grown and successful in the area and that they are needed for family consumption or to sell in the market. Sometimes there is a need for having several crops on the farm which will have different requirements.

The need for water harvesting may also be for environmental purposes. Restoring the degraded rangelands is a very good example. This can be an individual need at the farm or for a public projects at large scale which also have different requirements.

All those decisions on the area, the crop(s), the purpose and the extent of the water harvesting system should be clear and well established before any further steps are taken to design and implement the project. Not only that but whether water harvesting will work or not should be decided also at this stage. Here, the most important is the characteristics of the rainfall and the topography. Generally, in the Arab region, water harvesting is most suitable and needed in the zone from 100-400 mm annual. Of course, you can do water harvesting above 400 mm, but there will be less needs as rainfall may support most of the crops without water harvesting. In areas where rainfall is less than 100 mm, micro-catchment water harvesting is too risky as you may get several years with no rainfall and runoff. However, in this very low rainfall zone some macro-catchment practices such as surface reservoirs can be constructed specially to recharge groundwater aquifers.

**Step 2: Select the technique suitable for the site**

When you find that Micro catchment water harvesting is needed for the area and you select the crop to grow, then you need to select the technique(s) that is most suitable for both the crop and the conditions of your area.

If you plan to grow trees, then you need to think of the small basins (Negarim) or the semicircular bunds when slopes are gentile and soil is deep. But if you are in a mountainous area with steep slopes you may want to think of the contour bench terraces. However, for field crops such as cereals and legumes most suitable is runoff strips but some use contour ridges also for this. Field crops do not need deeper soil like trees. For restoring rangelands, one may think of contour ridges and bunds. Each crop and method have requirements to be successful, Table 1. Shows some of those requirements that may help selecting the technique.

**Table 1. Requirements for some micro catchment rainwater harvesting techniques and crops in the temperate dry areas**

| **Micro catchment techniques** | **Common crops** | **Preferred land slope %** | **Preferred soil depth (cm)** | **Preferred soil type** |
|---|---|---|---|---|
| **Contour ridges and bunds** | Shrubs and grasses, field crops, | 1-25 | ≥ 50 | Loamy sand to loam |
| **Semicircular bunds and Negarim** | Trees, shrubs | 1-15 | ≥ 100 | Loam to clay loam |
| **Runoff strips** | Field crops, grasses | 0.5-10 | ≥60 | Sandy loam to clay |
| **Contour bench terrasses** | Trees, shrubs and field crops | 25-65 | ≥100 | Loamy sand to loam |
| **Rooftop systems** | Domestic, livestock, home gardens | 0-100 | Not relevant | Not relevant |

**Step 3: Determine crop water requirements (ET)**

Water needs differ from crop to the other, from place to place and from time to time. There are several direct and indirect methods to determine crop water requirements. Most accurate include measurements using devices like Lysimeters, but also by adjusting pan evaporation data for various crops. Calculating crop evapotranspiration (ET) depends mainly on climatic parameters and crop specific adjusting coefficients. The scope of this manual does not include details of calculating crops ET or crop coefficients (Kc) but you may refer to FAO paper No 56 (FAO, 1998) which has all the details on estimating ET. For the purpose of this manual a lumped average monthly value of ET for major crop groups are approximated in Table 2. Not all cereals or legumes use the same ET and not all trees require same water amount, but those values may be sufficient for designing a sound micro-catchment water harvesting system. If one needs to be more precise then should use specific data for each crop and area which is available in all national research institutes in the Arab region.

Please not that those values approximate the total requirements of a crop and not the amount to be provided by water harvesting. Part of those requirements is provided directly by natural rain. For example, if we want to grow wheat in area with annual rainfall of 250 mm then the amount to be harvested, which is the deficit to be supplied by rainwater harvesting should be 500-250 = 250 mm.

**Table 2. Estimated water requirements grossly averaged for some crop groups in the rainfed and badia ecosystems (mm)**

| | Cereals | legumes | Trees | Grasses | Shrubs | Vegetables |
|---|---|---|---|---|---|---|
| **Jan** | 65 | 45 | 20 | | 10 | |
| **Feb** | 125 | 100 | 25 | 10 | 10 | 30 |
| **March** | 155 | 150 | 35 | 40 | 20 | 65 |
| **April** | 75 | 75 | 45 | 110 | 55 | 115 |
| **May** | - | - | 50 | 115 | 45 | 110 |
| **June** | - | - | 65 | 20 | 45 | - |
| **July** | - | - | 65 | - | 35 | - |
| **August** | - | - | 60 | - | 30 | - |
| **September** | - | - | 55 | - | 13 | - |
| **October** | - | - | 35 | - | 12 | - |
| **November** | - | - | 25 | - | 8 | - |
| **December** | 50 | 45 | 20 | - | 7 | - |
| **Total** | **470** | **415** | **500** | **295** | **290** | **320** |

**Step 4: Determine design annual rainfall (R)**

The design rainfall (R) is the amount of rainfall occurring during the cropping season at which or above the catchment area will provide sufficient runoff to satisfy the crop water requirements. The assigned design rainfall is expected to be equaled or exceeded at a selected level of dependability (i.e. exceedance probability). Choosing a design annual rainfall of 200 mm at a 70% exceedance probability, means that the annual rainfall in this location is expected to be 200 mm or more in 7 out of 10 years (in the other 3 years it will be lower than 200 mm). Similarly, design monthly or weekly rainfall can be evaluated but generally we use annual values. Usually a 67% (2/3) probability of exceedance is used for the design of agricultural water harvesting systems. On the conservative side when one chose too high probability then a lower design rainfall is selected. This will require that the catchment area be larger (over design of the system) which will cost more in land and in preparing the catchment. If however, a too low probability is selected then a high design rainfall will be used and result in a small catchment area with less water harvested in most of the years. In this case a risk of not having enough runoff water for the crop is high. Table 3 shows calculated values for some stations in Jordan.

**Table 3. Amount of annual rainfall with calculated probabilities of occurrence or exceeding 25%, 50%, 67% and 75% in some stations for illustration.**

| Station | No of years (N) | Mean annual rainfall (mm) | Probability 25% | probability 50% | Probability 67% | Probability 75% |
|---|---|---|---|---|---|---|
| **Muwaqqar** | 61 | 154 | 193 | 146 | 129 | 116 |
| **Sahab** | 51 | 254 | 294 | 235 | 203 | 193 |
| **Yaduda** | 47 | 313 | 369 | 300 | 262 | 253 |
| **Wadi shueib** | 59 | 355 | 432 | 346 | 279 | 254 |

| | | | | | | |
|---|---|---|---|---|---|---|
| **Na'ur** | 72 | 442 | 571 | 409 | 369 | 326 |
| **Ajlun** | 77 | 632 | 749 | 641 | 558 | 500 |
| **Hummar** | 57 | 509 | 587 | 482 | 398 | 378 |

To calculate design rainfall at any selected probability one may follow the following procedure (Critchley et al 1991).

- Obtain the values of mean annual rainfall from the nearest weather station for at least 10 years
- Rank the annual rainfall values from the highest value, given the number m=1 to the lowest value (if you have 15 years data) m=15. See table 4.
- Apply the following equation (1) to calculate the probabilities for each of the annual values in the table.

**P(%)= (m-0.375) / (N+0.25) * 100** **(1)**

Where: P = the probability in % of the observation of the rank (m) and N= the total number of observations.

For example, year 2012 in table 4 has annual rainfall of 390 mm and ranked m= 11 while we have data for 15 years N=15. Then applying the above equation:

P%= (11 -0.375)/(15+0.25)*100 = 69.7%

This means that the probability of having 390 mm is 69.7%.

**Table 4. Station annual rainfall for 15 years ranked and probability of occurrence calculated for each value.**

| **Year** | **2020** | **2016** | **2011** | **2006** | **2009** | **2015** | **2013** | **2008** | **2017** | **2010** | **2012** | **2018** | **2019** | **2014** | **2007** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Annual Rain** | 798 | 702 | 669 | 592 | 551 | 499 | 472 | 446 | 425 | 410 | 390 | 352 | 331 | 283 | 225 |
| **Rank (m)** | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
| **Probability (P%)** | 4.1 | 10.7 | 17.2 | 23.8 | 30.3 | 36.9 | 43.4 | 50.0 | 56.7 | 63.1 | 69.7 | 76.2 | 82.8 | 89.3 | 95.9 |

One however, may want to use a different probability as a design rainfall. In this case you need to follow the following procedure:

- Plot the data in table 4 on a log-log graph with rainfall amounts on the Y axis and P on the X-axis (red dots). Then draw the regression line which as a straight line. Use your judgment to approximate the regression line as shown in figure 14
- By selecting a specific probability on the X-axis (say 67%) then moving up to meet the regression line then horizontally to the Y-axis to find that the design rainfall to use in your area is about 370mm and for P=33% same thing with design rainfall is about 530 mm (dashed blue lines). You

can also determine P% for any rainfall amount using same procedure.

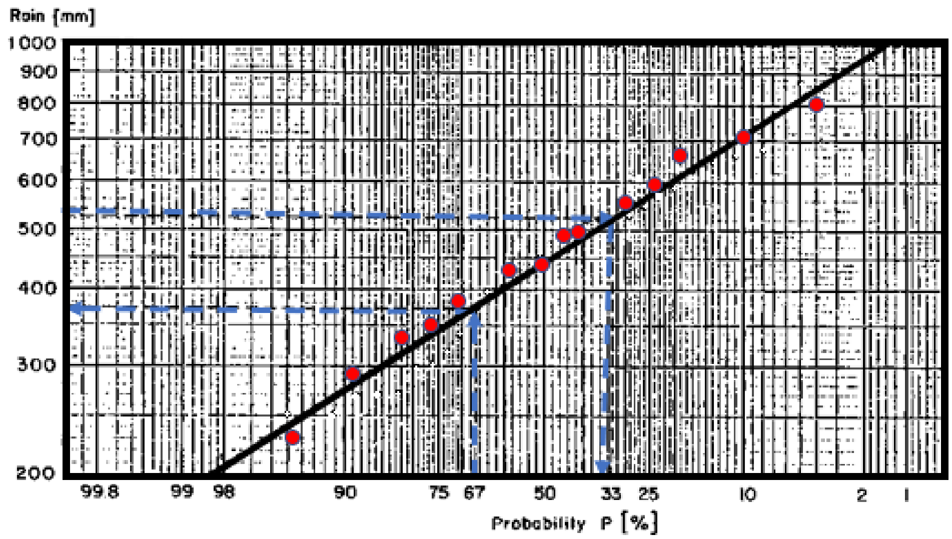



Figure 14. Log-log graph for determining the design rainfall at any selected probability of exceedance. (Adapted from Critchly et al 1991)

**Step 5. Determine design water storage capacity**

Soil has the ability to retain or hold water around its particles. This retention or storage capacity depends on soil type (texture) and soil structure. Coarse-textured soils such as sandy soils allow quick infiltration of precipitation but have low ability to hold water, thus are characterized by small water storage capacity. Medium textured soils (loams) are good as a cropped area due to their high-water holding capacity and moderate infiltration capacity.

Total water storage capacity of any soil, measured as "field capacity", does not mean that all of it is available to the plant. Plants withdraw soil moisture to meet their transpiration (T) demands based on weather conditions and plant physiological traits. Evaporation "E" also occur mainly from soil surface in response to climatic conditions. The total water withdrawal from the soil "E+T" rate determines how much and how fast water is taken up from the soil by plants.

It becomes more and more difficult for plants to withdraw water as the soil becomes drier, until the plants can no longer withdraw soil moisture, then they wilt and if water is not added will later die. The soil moisture level when a crop wilt is called the "wilting point". For most plants, water must be added to the soil before it dries to this level in order for plants to perform well. The difference in soil water between the field capacity and the wilting point is called the "plant available water". A given plant will use water at the same rate regardless of soil texture, but it will run out of water sooner in a sandier textured soil.

Table 5. shows the soil water approximated for different textured soils when they are fully wet (at field capacity), at wilting point and plant available water which is the difference between the two. *The later in % multiplied by the soil volume is the design water storage capacity.*

**Table 5. Average soil water holding capacity and plant available water in various textured soils.**

| **Soil Texture** | **Total soil water storage capacity (at Field Capacity)** | | **Unavailable water for plants (at Wilting Point)** | | **Available Water Holding Capacity** | |
|---|---|---|---|---|---|---|
| | % by volume | mm/m of soil | % by volume | mm/m of soil | % by volume | mm/m of soil |
| Coarse sands | 7.0 | 70 | 2.0 | 20 | 5.0 | 50 |
| Fine sands | 10.0 | 100 | 3.0 | 30 | 7.0 | 70 |
| Loamy sand | 15.0 | 150 | 5.0 | 50 | 10.0 | 100 |
| Sandy loam | 20.0 | 200 | 6.0 | 60 | 14.0 | 140 |
| Loam | 25.0 | 250 | 7.0 | 70 | 18.0 | 180 |
| clay loam | 30.0 | 300 | 10.0 | 100 | 20.0 | 200 |
| clay | 40.0 | 400 | 21.0 | 210 | 18.0 | 190 |

The depth of the soil is another important factor influencing water storage. Soil less than 0.5 m will hold too little water to support plant growth during extended dry periods. A depth of 0.5–1.0 m is acceptable; and more than one meter is even better. Soil depth may also be associated with plant root depth as the later will be limited by the soil depth***. Root depth (m) multiplied by root area (m2) makes the total soil volume (m3) that can hold water for the plant.***
Understanding how much water can be stored in the soil profile and be available for the crop is vital in evaluating the storage capacity for the water harvesting system. It is soil texture dependent but also depends on the extent of the crop rooting system, both in depth and in diameter. The deeper and wider the rooting system the larger the storage capacity. One should look at both soil texture and depth in relation to crop root system to determine the total water storage soil can provide for the plants. Table 6 shows crop root depth and diameter for major crop groups grown in the Arab region.

**Table 6. Average effective root depth and diameter of some crop groups in dry environments**

| **Crop** | **Effective average root depth (m)** | **Effective average roots diameter (m)** |
|---|---|---|
| **Trees** | 1.2 | 1.0-4.0 |
| **shrubs** | 0.8 | 0.5-1.5 |
| **Cereals** | 1.0 | Continuous |
| **legumes** | 0.6 | Continuous |
| **vegetables** | 0.7 | Rows of 1.0 m wide |
| **grasses** | 0.5 | Continuous |

For example, a tree in a loam soil with available water holding capacity (from table 5) of 0.18, a root zone depth of 1.2m and a root area of 7.0m2 the soil storage capacity would be the total volume of the root system multiplied by the available water holding capacity: 7m2*1.2m*0.18= 1.512 m3 of water can be stored and used by the tree if filled to the field capacity. This would be the soil storage capacity. Plants in earlier stages of growth may not have the maximum root depth so transitional root depth should not be considered for design purposes and only root depth at peak plant development should be considered.

But this is not all the potential water storage in the soil. During the rainy season, and while water is being stored from rain and runoff, the plants are depleting some of the stored water through ET, emptying part of the soil reservoir and allowing for more storage. So, the total ET during the rainy season may be added to the original soil water storage capacity to make the system design storage. For example, the rainy season for trees extends normally from November to April. From table 2 total ET during those months is 170mm (0.17 m). Using the example above the emptied volume would be: 0.17 m (ET)*7.0m2 (root area) = 1.19 m3. This amount can be added to the soil storage capacity calculated above of 1.51 to have a "Design Storage" of 2.71m3.

**Step 6: determine design runoff coefficient (RC)**

As indicated earlier, runoff coefficient is the ratio of annual runoff to annual rainfall. It varies with rainfall intensity and duration so different storms will have different runoff coefficient**. *For design however, we need one value that averages the runoff coefficients for the whole rainfall season*.** ***This is the average runoff volume of the season divided by design seasonal rainfall.*** This can be measured in the field during several years or by using rainfall simulators or using models designed for this purpose. For our purposes we will use approximations from other similar areas of the world.

Furthermore, runoff coefficient depends on the soil type, the slope and the catchment surface condition. We know that the heavier the soil, the steeper the slope and the smoother the surface the higher the runoff coefficient and vice versa. Table 7 shows approximate values for runoff coefficients you can use for the design of the micro-catchment systems with runs not more than 50m.

For example, if you want to design a micro catchment system in the badia of Jordan which has almost a bare loamy sand soil and a slope between 0.5-5%, then from the table 7 below you can use an average RC of 0.18. Would you want to select a design RC for wheat cropped area in Irbid which has a loamy soil with slope less than 0.5 then RC would be 0.18.

**Table 7. Potential runoff coefficients (RC) for various land uses, soil types and land slopes in the Arab region rainfed and rangelands environments**

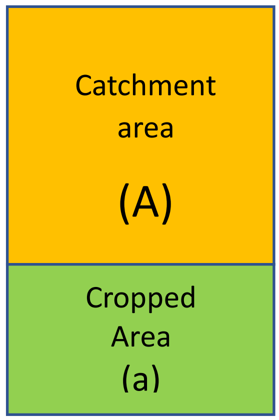
| Land use | Slope% | Soil group A% | Soil group B% | Soil group C% | Soil group D% |
|---|---|---|---|---|---|
| **Forest/orchard** | ≤0.5 | 1 | 6 | 15 | 16 |
| | 0.5-5 | 3 | 8 | 17 | 18 |
| | 5-10 | 6 | 11 | 20 | 21 |
| | ≥10 | 10 | 15 | 20 | 25 |
| **Grass** | ≤0.5 | 6 | 11 | 20 | 21 |
| | 0.5-5 | 8 | 13 | 22 | 23 |
| | 5-10 | 11 | 16 | 25 | 26 |
| | ≥10 | 15 | 20 | 30 | 32 |
| **Crops** | ≤0.5 | 11 | 16 | 25 | 26 |
| | 0.5-5 | 13 | 18 | 26 | 28 |
| | 5-10 | 16 | 21 | 30 | 31 |
| | ≥10 | 20 | 25 | 34 | 35 |
| **Bare soil** | ≤0.5 | 16 | 21 | 30 | 31 |
| | 0.5-5 | 18 | 23 | 32 | 33 |
| | 5-10 | 20 | 26 | 35 | 36 |
| | ≥10 | 25 | 30 | 40 | 42 |
| **Solid surface** | All | 90-100 | | | |

*Soil group A (Sand, loamy sand and sandy loam), Soil group B (silt loam to loam), Soil Group C (sandy clay loam), Soil group D (clay loam, silty clay loam, sandy clay, silty clay and clay)

**Step 7: Determine catchment/target ratio (A/a)**

The ratio of the area of the catchment to that of the target or cropped area is probably the most important to determine for micro catchment techniques. As indicated earlier the catchment area should be enough to provide the cropped area with additional water to cover the deficit between crop water requirements and the design rainfall. The ratio can be calculated from the following equation:

A/a = (ET-R)/(R*RC)
Where:
A: is the Catchment area
a: is the Target area
ET: is the crop water requirements
R: is the Design Rainfall
RC: is the Runoff Coefficient




For example, if we want to design runoff strips for barley in area with design rainfall of 200 mm and RC of 25%. Barley water requirement is 470mm from table 2. Subtracting annual rainfall of 200 mm, will have a deficit of 270 mm annual. If we divide this by the expected runoff which is the annual rainfall multiplied by runoff coefficient (200mm*0.25), we will have a catchment target ratio of 5. Means that the catchment should be 5 times the target. So, if we have 1 m wide strip cropped with barley, we should have 5m wide catchment strip upstream to ensure that barley will receive 470 mm. Of course, because rainfall vary from one year to the other and that we cannot change the ratio every year we expect that the barley crop will in some years receive less water and in others receive more water. This may not be a serious problem if the differences are not too large.

**Step 8. Check if the soil storage capacity can accommodate the runoff**

Once we determine the A/a ratio we know how much water will flow from the catchment to the cropped area.  We determined the water holding capacity of the soil profile earlier and determined to the best available information that rainwater and runoff nearly all will be stored and used by the crop. However, one cannot predict the future 100% and some deviations from the design can occur. Tracking the water already in the soil and how much space available to receive more water is not an easy task. One can measure soil water frequently or install soil moisture detection device to determine the soil water status. Other complication is associated with the variable depletion of water from the soil in ET during the rainy season which allows more space for more runoff. As runoff occurs at several storms during the rainy season one need to evaluate the storge capacity before each storm which is a bit complicated. There are models however, to handle water balance but it is beyond the scope of this manual.

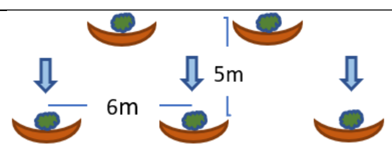
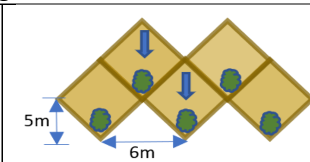
The most practical way is to assume that soil's status at the beginning of the season is near the level of wilting point. And the available initial storage to fill is the difference between that at field capacity level and wilting point level (see table 5). For example, a tree having soil depth of 1.2 m and the soil is clay loam, then available storage is 180mm*1.2= 216 mm. those can be filled immediately at the beginning of the rainy season. More space will be available during the season as plants grow and use some of the stored water.

If we get more runoff than soil storage capacity then the extra water will be lost in deep percolation below root zone. Of course, this is not an absolute loss as lost water may join ground water aquifers. If we get less runoff than soil storage capacity the crop may suffer some stress. In this case we ger less yield than optimal which is normal in all rainfed areas and rangelands of the dry areas. However, the yield will still be much higher than the case without water harvesting.

In cases where soil storage capacity is low, as in sandy soils, and that the soil is shallow, one may get in a situation where storage capacity is not enough to provide the crop with minimum amounts for an economic yield. In this case we should not proceed with rainwater harvesting as an option unless we can increase soil storage capacity. Adding water absorbent polymers to the soil, in the case of cash crops like vegetables and some trees during the planting can substantially increase the amount of water the soil can hold. This of course is at a cost and an economic analysis should performed to determine if feasible.

## 2. Practical design example

Following are three design examples for the cases of rangeland restoration, trees micro-catchments and field crops with runoff strips. The examples are for conditions in Jordan but may be applied for any area in the Arab region or the dry areas.

| **Table 9. Practical design example 2. Olive orchard with semicircular bunds & small basins** | | |
|---|---|---|
| **Step 1** | Determine the need and potential for water harvesting | Olives trees in Jerash areas is grown in annual rainfall zone of 300-400 mm at times when olive trees need 500 mm annually. Trees survive the deficit but yields are low and fluctuate greatly from one year to the other. Availability of supplemental water through water harvesting will improve yields and provide more stable income and higher oil quality. |
| **Step 2** | Select the technique and the suitable site | A site in Jarash area with mean annual rainfall of 400 mm is selected on land with a slope of 5% having deep (1.5 m) clay loam soils. Consulting with table 1 suitable techniques are semicircular bunds and small basins (negarim) |
| **Step 3** | Determine crop water requirements and water deficit | From table 2. trees ET is around 500 mm. Rainfall of 400 mm the deficit would be 100 mm |
| **Step 4** | Determine design annual rainfall | Annual rainfall at 67% probability in the area was calculated by the equation to be 320 mm |
| **Step 5** | Determine design water storage capacity | - From table 5. A clay loam soil has 20% available water.<br>- Olive matured trees is 3 m diameter (7m2 area) and 1.5 m soil depth.<br>- Available water per tree = 7.0m2* 1.5m * 20%= 2.1 m3 |
| **Step 6** | Determine design runoff coefficient | For clay loam soil with slope of 5%, from table 7 Orchards similar to forest RC = 21% is suitable. |
| **Step 7** | Determine catchment /target ratio (A/a) | Applying the equation: A/a = (ET-R)/(R*RC)<br>- ET= 500 mm, Design R= 320, RC= 21%<br>- A/a = (500-320)/(320*0.21)= 2.7, may be rounded to 3 then A/a = 3:1<br>- As the target area/tree is 7m2 then the catchment area should be 21m2<br>- Total area of catchment and target =7+21=28 m2 so best-rounded tree spacing = 6m x 5 m |
| **Step 8** | Check if the soil storage capacity can accommodate the expected runoff and rainfall | - Catchment area= Total tree area-Target area=(5m*6m)-(7.0 m2)= 23m2<br>- Runoff volume= Catchment * rainfall * Runoff coefficient= 23.0m2*0.32m*.20= 1.47 m3<br>- Rainwater volume on target= Rainfall depth * area = 0.32 m*7m2= 2.24 m3<br>- Total water expected at target = Runoff volume + Rainfall volume = 1,47+ 2.24= 3.71 m3<br>- Storage capacity in soil profile= tree area*soil depth*available WHC = 7.0m2*1.5m*0.2=2.1m3.<br>- Depleted ET volume from November to April Table 2 = ET (0.170m)*tree area (7.0m2)= 0.17m*7.0m2=1.19m3<br>- Total storage available=available WHC + depleted ET= 2.1+1.19 m3= 3.29 m3.<br>This is a bit short of 3.71 m3 of water expected but within the error margin |
| **Summary** |   | Olive trees planted at spacings on 5x6 meters with semicircular bunds/small basins would provide the trees with supplemental water to cover the deficit between rainfall and crop ET.   |