A New Approach for Planning M.C.W.H. Systems with Annual Rainfall-Runoff Data

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Abstract: In this study a new approach for planning Micro-Catchment Water Harvesting (M.C.W.H.) systems for irrigation in semi-arid regions such as the Aegean islands, is presented. M.C.W.H. is a cheap solution for constructing irrigation infrastructure with zero energy cost in regions where water is scarce. The proposed approach introduces simple linear relationships for estimating the annual volume of water V_s collected mainly from the CA (Contributing Area), stored in the root zone (Infiltration Basin, IB), according to the annual rainfall and runoff depths, after having determined the ratio of areas of micro-catchment (MC) components i.e. $\lambda = A_{CA}/A_{IB}$ and its whole area A_{MC}. This procedure was applied in Paros island of the Cyclades complex in the middle of the Aegean sea in east Mediterranean. Besides, income-cost analysis was performed via NPV method for almond, peach and apricot trees. The new approach was proved versatile and easy to use. Besides, the investment turned out to be advantageous two years after the MCs construction.

Key words: M.C.W.H., semi-arid regions, rainfall, runoff, V_s, λ, A_{MC}.

1. INTRODUCTION

In many regions of southern Europe (e.g. in most east Mediterranean islands), water is not enough for intensive irrigation development. In some other cases, due to various technical and economic reasons, water cannot be transferred over long distances. As a result, large areas remain without irrigation water and therefore, they are solely dependent on rainfall (Tsakiris 1991). In order to increase the availability of water for crop production, several types of Rain Water Harvesting techniques (RWH) are used. One of the most common is Micro-Catchment Water Harvesting (M.C.W.H.), which is a method for inducing, collecting, storing and conserving local surface runoff for agriculture in arid and semi-arid regions (Boers and Ben-Asher 1982, Giakoumakis 2008). M.C.W.H. is a likely viable option to increase water productivity at the production system level. M.C.W.H. and similar techniques have a significant potential for improving and sustaining the rainfed agriculture in the region of application.

M.C.W.H. is not a recent discovery. Throughout history, archaeological evidence has revealed M.C.W.H. sites that were implemented in arid environments (annual rainfall less than 200 mm) such as Jordan, the Negev desert in Israel, Syria, Tunisia and Iraq. The earliest signs of M.C.W.H. are believed to have been constructed over 9000 years ago in the Edom Mountains in southern Jordan (Adham et.al. 2016).

Low rainfall, water scarcity and land degradation severely intimidate the production capacities of the rangelands in the arid environments. Surface crusting by raindrops helps generating frequent local runoff on degraded sloping land, but it is generally lost in transmission and seldom flows down to streams. Micro-catchments can capture local runoff, reduce transmission losses and concentrate it into the plant basins. Thus, an efficient water harvesting planning is necessary for increasing the runoff production potential of micro-catchments and water storage capacity of the soil in the plant basins (Ali et al. 2007, Ali et al. 2010).

The purpose of the present paper is to assess the effectiveness of M.C.W.H. technique in a semi-arid environment using here a new approach for planning the system, based on annual rainfall and runoff data. Paros island of Cyclades in the middle of the Aegean sea was selected as region of application. The proposed approach can also be used without any changes, in arid environments.

2. METHODS

For determining design criteria in a M.C.W.H. system, the following was considered:

1. Based on measured annual rainfall data, design rainfall for a given return period (i.e. T=8 years, FAO 1991) is derived.

2. From the design rainfall, annual runoff is calculated via SCS-CN model (SCS 2004). The latter has the advantage of incorporating rainfall losses as a function of CN number (Wanielista 1990) and it is preferable than other simplistic approaches (i.e. linear runoff model) in case of lack of runoff data as in the present study. Other more complex rainfall-runoff models for designing M.CW.H. systems are used for single rainfall events such as the Kinematic Wave Equation and experimental data are necessary for comparison purposes (Giakoumakis and Tsakiris 2001).

3. The annual water balance in the IB (Infiltration Basin) is a valid hypothesis, taking into account that rainfall in semi-arid regions occurs mainly during the wet period of a hydrologic year (from October to April) and almost not at all during the dry period.

A micro-catchment is composed from the Contributing Area (CA) where runoff occurs and the Infiltration Basin (IB) where water is stored directly in the root zone for crop requirements (Fig. 1).

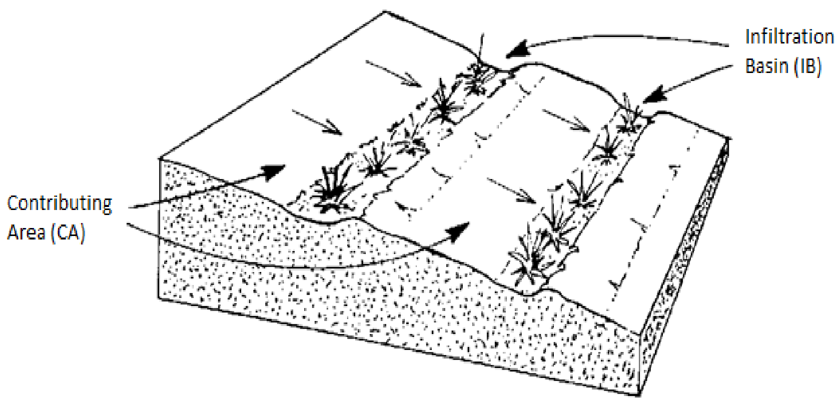


Figure 1. Typical micro-catchment and its components (strip form IB), (FAO 1991).

The annual runoff volume from CA to IB (m^3) is given by:

$$V_{CA} = 0.001 \cdot R \cdot A_{CA} \qquad (1)$$

where:

R: runoff from CA (Contributing Area), (mm)

A_{CA}: area of CA (m^2)

The annual volume of water from rainfall P in the IB is:

$$V_{IB} = 0.001 \cdot P \cdot A_{IB} \qquad (2)$$

where:

P: annual rainfall, (mm)

A_{IB}: area of IB (m^2)

If p is the percentage of volume of water infiltrating into IB and lost as deep percolation losses or/and evaporation from soil surface, the water volume finally stored in the IB is:

$$V_s = (1-p) \cdot (V_{CA} + V_{IB}) \quad (3)$$

However, the annual volume necessary for crop water requirements in the IB is given by:

$$V_{RE} = 0.001 \cdot ET_c \cdot A_{IB} \quad (4)$$

where:

ET_c: potential evapotranspiration of the crop (mm).

Thus, for an effective planning it should be $V_s = V_{RE}$ Taking into account eqns 1, 2, 3 and 4, one obtains:

$$A_{CA}/A_{IB} = [ET_c - P \cdot (1-p)]/[(1-p) \cdot R] \quad (5)$$

From eqn 5 the ratio $\lambda = A_{CA}/A_{IB}$ of areas of CA and IB can be calculated.

If A_{MC} is the total micro-catchment area in m^2, then:

$$A_{MC} = A_{CA} + A_{IB} \quad (6)$$

Writing $\lambda = A_{CA}/A_{IB}$, from eqn 6, A_{CA} and A_{IB} can be expressed as follows:

$$A_{CA} = A_{MC} \cdot [\lambda /(1+\lambda)] \quad (7)$$

and

$$A_{IB} = A_{MC} \cdot [1 /(1+\lambda)] \quad (8)$$

Combining eqns 1, 2,3, 7 and 8, yields:

$$V_s = 0.001 \cdot A_{MC} \cdot (P + R \cdot \lambda) \cdot [(1-p)/(1+\lambda)] \quad (9)$$

Eqn 9 can be viewed as a key-relationship, expressing the annual volume of water stored in the IB (m^3) as a linear function of the total MC area, A_{MC} (m^2), with parameter λ being calculated from eqn 5 for given annual rainfall and runoff depths, P and R (mm), respectively.

3. STUDY AREA

The above was applied in Paros island in the middle of the Aegean sea (latitude 37° 5', longitude 25° 14'), (Fig. 2). Although climatologicl conditions are appropriate for applying the M.C.W.H. technique for irrigation, agricultural areas of the island are fed by drillings, leading to the lowering of underground water level, increasing so the risk of salt water intrusion.

Figure 2. Paros island and selected (dot) region's location for M.C.W.H application

So, it was decided to select this island as a pilot region in order to prove that M.C.W.H. technique may resolve with low cost the local irrigation problem and save so invaluable underground water resources for other uses (i.e. drinking water after treatment). The region selected has an area of 7 ha (200·350 m). Its position (in the north of the island, near Longovardas monastery) is illustrated in Figure 2. It is ideal because all of the criteria for the installation of a M.C.W.H. system are fulfilled (Rands 1980). Namely:

1. Soil slope between 2 and 8%
2. Medium soil texture
3. Soil depth greater than 1.5 m
4. Not cultivated land
5. Area of a few ha

4. RESULTS AND DISCUSSION

From the categories of M.C.W.H., the strip farming was selected because it is easily constructed and well adapted in an inclined surface like the chosen one.

From the local station of National Meteorological Service having the same altitude as the mean one of the selected area (i.e. 32 m a.s.l), a time series of annual rainfall date was used for the last 30 years. It was shown via x^2 test that these data are well adapted to a normal distribution with mean value P_m=560.8 mm and standard deviation s=171.5 mm. The well-known frequency factor relationship was used for determining design rainfall depth, which, for a normal distribution is written as:

$$P_T = P_m + s \cdot z \qquad (10)$$

Where P_T is the design rainfall depth (mm) for a return period T and z is the variable of the unit normal distribution:

$$z= (P- P_m)/s \quad (11)$$

According to FAO (1991) a return period of 8 years was chosen. This corresponds to an exceedance probability of 0,125 and thus z= -1.15. From eqn 10 one obtains $P_{T=8}$=363.5 mm.

Using then SCS-CN model for initial losses 20% of the total with CN=94 (Wanielista 1990) for a bare soil surface in the CA having previously been treated in order to minimize soil infiltrability (category D), the corresponding total losses S were calculated as equal as 16.2 mm and annual design runoff depth R was then derived as equal as 344.7 mm. The following relations have been used:

$$R=(P-0.2\cdot S)^2/(P+0.8\cdot S) \text{ for } P>0.2\cdot S \quad (12)$$

$$R=0 \text{ for } P\leq 0.2\cdot S$$

where:

P: rainfall depth (mm)

R: runoff depth (mm)

S: total losses (mm) given by (SI units): S=(25.400/CN)-254

Reference potential evapotranspiration was calculated via Thornthwaite formula because that only mean monthly temperature and sunshine duration data were available from the nearby meteorological station, that is the unique in the island. Monthly crop coefficients from April to October for the arboricultures selected (i.e. almond, peach and apricot trees) were found in the literature (Pontikis 1997). The annual values of crop evapotranspiration were as equal as ET_c=432.4 mm for almond trees, whereas ET_c=603.7 mm for peach and apricot trees.

Substituting the corresponding values of ET_c, P and R in eqn 5 with p=0.3, which sounds logical for medium texture soils, the λ ratio for the MCs was calculated:

$\lambda=A_{CA}/A_{IB}$= 0.7 for almond trees and $\lambda=A_{CA}/A_{IB}$=1.5 for peach and apricot trees.

Thus, from eqn 9 one obtains:

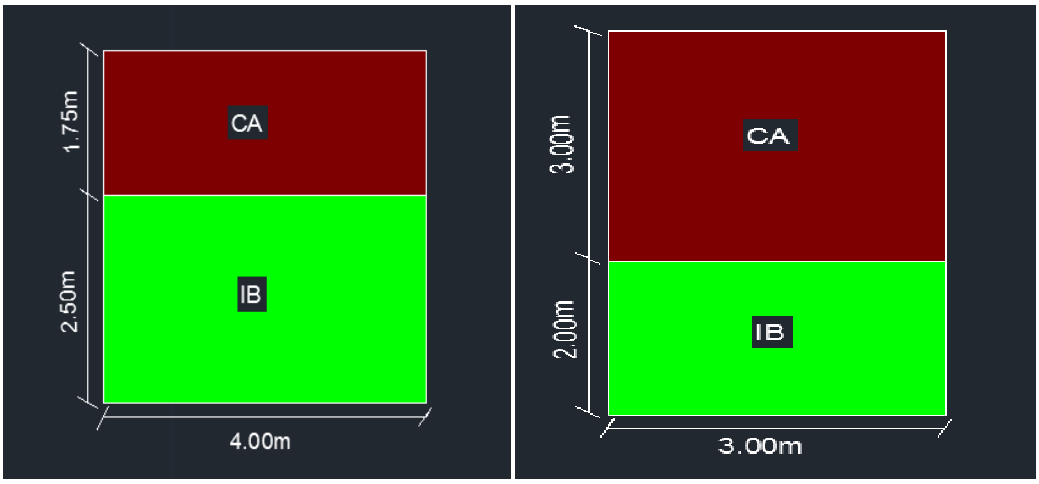
$$V_s= 0.25\cdot A_{MC} \quad (13)$$

for almond, peach and apricot trees. Thus, the annual volume of water V_s expected to be stored in IB, equals for each kind of trees, the 25% of the total MC area.

Taking into account that for almond trees the root zone for each tree is of minimum diameter 2.3 m and that distance between trees should not be less than 4 m (Pontikis 1997), the proposed IB dimensions for this arboriculture are: 2.5 m length and 4 m width, or A_{IB}=10 m^2. With computed $\lambda=A_{CA}/A_{IB}$= 0.7, the area of the CA should be 7 m^2 with the same width as previously (i.e. 4x1.75 m). So, each MC in total will be 17 m^2. According to eqn 13, the expected annual stored volume of rainwater per IB for crop water requirements can reach 4.25 m^3.

Besides, taking into account that for peach and apricot trees the root zone for each tree is of minimum diameter 1.8 m and that distance between trees should not be less than 3 m (Pontikis 1997), the proposed IB dimensions for this arboriculture are: 2 m length and 3 m width, or A_{IB}=6 m^2. With computed $\lambda=A_{CA}/A_{IB}$= 1.5, the area of the CA should be 9 m^2 with the same width as previously (i.e. 3x3 m). So, each MC in total will be 15 m^2. According to eqn 13, the expected annual stored volume of rainwater per IB for crop water requirements can reach in this case 3.75 m^3.

MC's dimensions are illustrated in Figures 3a and 3b for almond and peach-apricot trees, respectively.



a. b.

Figure 3. MC's dimensions for: a). Almond trees b). Peach and apricot trees

A rural road network will be constructed in the chosen area of 7 ha and so, the net irrigated will be of 6.6 ha or 2.2 ha per arboriculture. Thus, 22.000/17= 1.294 almond trees will be planted, also 22.000/15=1.467 peach trees and 1.467 apricot trees (Fig.4).

Figure 4. Region of application

The cost of construction is summarized in the following Table:

Table 1. Cost of construction (€)

Category	
Earthworks + CAs surface treatment	21.000
Trees purchase and plantation (*)	85.000
SUM	106.000

(*) All kind of trees will be three year old for giving fruits immediately (Pontikis 1997).

The estimated total annual cost for fertilizers, pesticides and pruning for 4.228 trees is 10.000 €.

For almond trees the mean annual production is 10 kg/year/tree with selling price from the producer 6 €/kg (Nanos 2018). For peach trees 40 kg/year/tree with 0.3 €/kg and for apricot trees 35 kg/year/tree with also 0.3 €/kg (Tavoularis 2012). Thus, the annual income for the producer is expected to be (Table 2):

Table 2.Annual income (€)

Category	
Almond trees	*6.0·10·1.294=77.640*
Peach trees	*0.3·40·1.467=17.604*
Apricot trees	*0.3·35·1.467=15.404*
SUM	110.648

Economic evaluation of the application of the M.C.W.H. technique was performed by the well-known NPV (Net Present Value) method (Tsakiris 2006):

$$\mathrm{NPV}(i,N)=\sum_{t=0}^{N}\frac{R_t}{(1+i)^t} \qquad (14)$$

where:

t the time of the cash flow

i the discount rate

N the total number of periods

R_t the net cash flow (i.e. cash inflow – cash outflow), at time *t*.

i=10% (mean value for reclamation works in Greece).

Results from eqn (14) are presented in Table 3:

Table 3. NPV (€)

Year	Cash outflow	Cash inflow	R	NPV
0	106.000	0	-106.000	-106.000
1	10.000	110.648	100.648	91.498
2	10.000	110.648	100.648	83.180
SUM				68.678>0

From Table 3 one concludes that the investment is advantageous two years after the MCs construction (i.e. SUM>0).

5. CONCLUSIONS

In the present study a new approach for planning micro-catchments for the M.C.W.H. technique is proposed. After having determined the ratio λ of the areas of the components of each micro-catchment, the annual water volume expected to be stored in the root zone of each IB, can be estimated. The relevant relationships derived in this work, are of linear form and easily applied, provided that annual design rainfall and runoff depths are known. The new approach was applied in a region of Paros island of the Aegean sea with semi-arid climatic conditions. It was proved via NPV formula, that M.C.W.H. technique as irrigation method exploiting natural rainfall, is advantageous for the region, two years after the MCs construction.

6. REFERENCES

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