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Principles for designing endorheic microcatchments

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Abstract

Desertification resulting from edaphic aridity is a very frequent process on deforested slopes under Mediterranean conditions: a light vegetation cover accelerates water erosion and this, in turn, prevents the development of a sufficiently dense vegetation. It is a feedback process that takes many years to revert.

An approach for tackling this problem consists in ordering the actual high surface runoff and retaining it through a water-trap system. The design of endorheic microcatchments increases the infiltration into the slope, reduces surface runoff, diminishes water erosion and facilitates the adoption of measures to restore vegetation. Since moist conditions prevail in those areas receiving and holding runoff, the establishment and development of woody vegetation can be readily attained thus providing a chance of halting the desertification process (concept of *oasification*).

For the design of water harvesting structures ensuring a successful afforestation of arid lands (microcatchments, ridging, terracing), the concept of primary systematization is developed. This term refers to a unit area with two markedly different sections: one exporting surface runoff and the other collecting surface runoff by means of an appropriately sized micro-pond receiving the excess water.

At the core of this study lies the application of the local water balance both to the original (degraded) slope and to the systematized slope separating runoff producing from runoff collecting areas. The equations generated through this analysis make it possible to simulate the hydrological behaviour of any sloping land and to quantify the available water under different conditions and at specific points of an area intended for afforestation.

To assist in the use of these equations, they are spelt out with particular reference to two of the most common models in hydrology: Horton's infiltration equation and the curve number method. The resulting system of equations – fairly lengthy and elaborate in both cases – made computerization advisable. Thus, two programmes, HYDNUM and MODIPE, have been developed. The final part of the study is taken up by one example which show the potential usefulness of the first programme.

Key words

Desertification, water harvesting, systematized unit, micropond, endorheic microcatchment, reforestation of arid zones, *oasification*, hydrologic model

1. Introduction

A water harvesting system consists of two main parts: the area where surface runoff originates (runoff producing or contributing area) and the area where this excess water is collected and stored (runoff collecting or basin area). This collecting area should provide an improved microclimate for the establishment, growth and development of crops grown or seedlings planted there. (See Figure 1.)

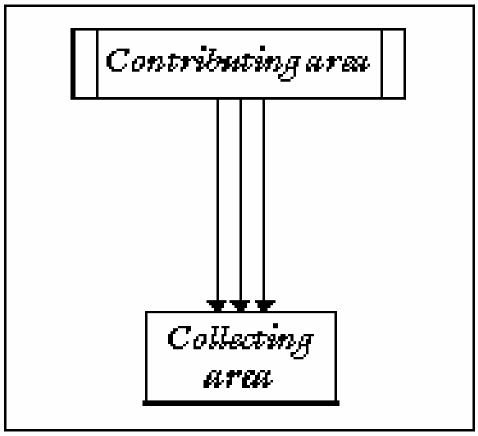

Figure 1: Outline of water harvesting

In trying to solve the problem, several methodological proposals have been put forward. The first simulation model for a cultivation technique incorporating the use of the surface runoff (the "desert strip farming" in the Arizona desert) appeared in the mid-1970s. From that time onwards, new and interesting models have been developed [ANAYA et al.(1976); SMITH (1978); BOERS et al. (1986); NAMDE (1987); ORON et al.(1987); VILLANUEVA et al. (1987); GIRÁLDEZ et al.(1988); CADOT (1989); HARI (1989); BOERS (1994); etc.] enabling us to better understand and design water harvesting systems.

All these models share the same basic approach. To satisfy the water requirements of the seedlings planted in the cultivated area, the contributing area must have an appropriate size. Hence, in the design of any water harvesting system, the water demands of the plants must be taken into account and the size of both the producing area (S_1) and the collecting area (S_2) must be defined, or a suitable relationship between them (S_1/S_2). The fundamental starting parameters for any design must be the local precipitation (not only its quantity but also its distribution) and the surface runoff caused by these rainfalls in the contributing area. Through a continuity equation, the working of the collecting area is simulated. It should always be borne in mind that by varying the surface of the contributing area, it may be possible to provide enough runoff volume to complete the water requirements of the crop.

Thus, the basic water balance that these agricultural methods propose may be expressed as follows:

$$\boxed{DESP = P + E_{s1}}$$

where P is the precipitation input, E_{s1} is the runoff furnished by the producing area, and DESP is the amount of available water in the collecting (or cultivated) area.

This balance can be worked out daily, weekly, monthly or every year. Precipitation data may be introduced as rainfall quantity or intensity. The runoff in the contributing area can also be calculated in different ways (runoff coefficients, the curve number method, linear regressions, the kinematic wave system, et cetera). On the other hand, the continuity equation may be completed with other input data of paedological (moisture holding capacity), physiological (water requirements of the crop, acceptable drop in soil moisture), hydraulic (flows, runnoff velocity) or economic-technical nature (implements' size, minimum surface cultivated and so on).

The simplicity of some of the models, particularly those seeking just approximate practical results (VILLANUEVA et al.), contrasts with the complexity of others aiming for accuracy and including a whole range of parameters (e.g. BOERS). But there are two important reasons why none of these models can be readily applied to the afforestation of arid lands: they do not consider the infiltration in the contributing area and they do not estimate the required size of the microponds.

Agricultural water harvesting systems try to create moister microclimates, oasis-like, where crops will thrive under improved conditions. The more impervious the producing area is, the greater its runoff efficiency will be. This may be achieved by means of physical, chemical or biological treatments (i.e. by compacting and smoothing the area; removing the stones from the surface; using salts, wax or asphalt; eliminating any vegetation; and so on). In forestry, however, the aims are quite different and, in any case, the runoff producing area behaves as such only to a certain extent, on a temporary basis. The water volume that infiltrates into this soil helps to re-establish the degraded slope, and makes the development of a permanent and more densely vegetated cover easier. For this reason, it must be quantified and even promoted.

Although these are important qualifications, the fundamental reason why the models developed so far are unsuitable for forestry practices results from the mistaken assumption that runoff water produced in the catchment area will necessarily infiltrate into the collecting area. As a matter of fact, this will not be the case unless some appropriately-sized water-traps are created in the collecting area (concept of microponds). During heavy precipitation events or storms, water will be prevented from infiltrating into the soil, all the more so when it accumulates in collecting areas. Admittedly, this simplification may be discounted when dealing with deep and very spongy soils in arable lands (though it will always be risky to accept it without further calculations and data). But this assumption is completely unacceptable for shallow undeveloped soils in degraded lands intended for afforestation.

2. Description of the model

Keeping in mind all the qualifications we have just mentioned, and from a surface hydrology standpoint, four equations must be taken into account for the development of a water harvesting model specifically relevant to forestry:

-1- $DESP = P + E_{s1} - E_{s2}$

-2- $PIMP = P - E_{s1}$

-3- $$PROM = \frac{PIMP \cdot S_1 + DESP \cdot S_2}{S_1 + S_2}$$

-4- $$\frac{dV}{dt} = I(t) - Q(t)$$

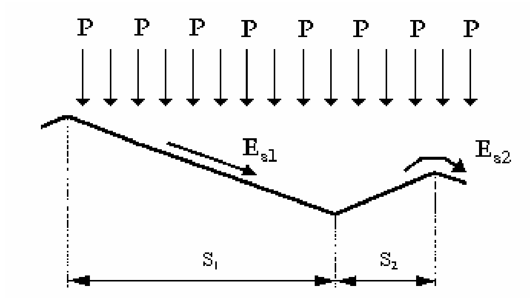

Figure 2

where: P is the precipitation of the analysed downpour;

DESP, the infiltration or the availability of water in the collecting area;

PIMP, the availability of water in the contributing area;

PROM, the average availability of water in the systematized unit (≈ in the slope);

E_{s1}, the effective rainfall or surface runoff generated in the contributing area;

E_{s2}, the surface runoff that escapes from the unit area;

S_1, the surface corresponding to the contributing area;

S_2, the surface of the collecting area;

S, the size of the unit area ($S = S_1 + S_2$ = 1/density of the afforestation);

$\frac{dV}{dt}$, the variation of the water volume accumulated in the micropond during dt;

I(t), the inflow rate;

Q(t), the outflow rate.

The correct ordering and harvesting of runoff water on sloping lands undergoing a desertification process due to paedological aridity (MARTÍNEZ DE AZAGRA & CALVO, 1996) should be part and parcel of any useful strategy to reverse the regressive succession threatening these ecosystems. Site preparation for afforestation purposes must be designed with the creation of collecting and contributing areas in mind. In fact, a great deal of soil manipulation techniques in forestry produce this effect by dividing the sloping land into plots where runoff contributing and runoff collecting areas can be identified (MARTÍNEZ DE AZAGRA, 1996). The resulting plots from the preparation of the land will be called systematized units.

On account of both the steep slope and the reduced size of these units ($S = S_1 + S_2 \leq 100\ m^2$), the time the water takes to circulate is very short (scarcely a few minutes). Therefore, it is not necessary to make use of the hydraulic equations for flow on sloping lands. On the other hand, it may be assumed that each systematized unit functions independently from the rest. Both hypotheses simplify the real course of events and they lead to results slightly inaccurate underestimating the actual infiltration taking place in the slope. But this may very well be acceptable if we want to err on the side of caution when we calculate water availability in an arid land.

The conceptual scheme of the functioning of a systematized unit is shown in Figure 3. It can be observed that it rains with an intensity i(t) which brings about an infiltration rate $v_i(t)$ in the contributing area [lower than the rainfall] and a runoff e(t) that feeds the collecting area. To ensure water harvesting, there is a micropond which accumulates the excess of water that cannot be infiltrated immediately. If the water sheet rises above the height H, the water overflows and it is lost out of the unit area. If not, the hydrological system becomes endorheic to that shower (E_{s2} = 0 mm).

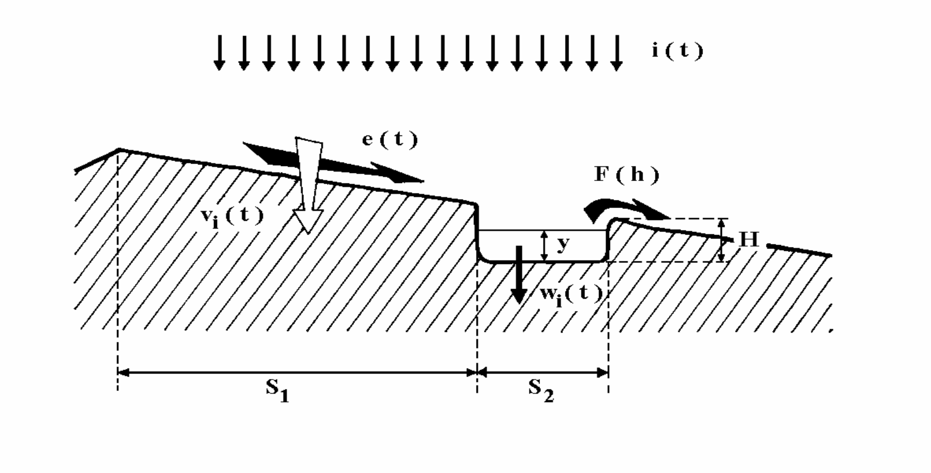

Figure 3: Functioning of a microcatchment with a mini-dam

Thanks to the independence hypothesis, the water volume infiltrated into the producing area (PIMP), may be easily worked out:

$$\boxed{\text{PIMP} = \int_0^D v_i(t)\cdot dt = \int_0^D \left[i(t) - e(t)\right]\cdot dt}$$

where D is the rainfall duration, $v_i(t)$ is the water infiltration rate in the contributing or runoff area, i(t) is the rainfall intensity and e(t) is the runoff intensity produced by the rainfall.

As it may be inferred from this equation, the possibility that the infiltration process can last longer than the precipitation event, is not taken into account. In other words, we assume a runoff area without any depressions that may have stored some water. It is not considered either the possibility that a part of the effective rain, produced at a period of time, can infiltrate into the same runoff area when the rainfall intensity has dropped; this is because the transition time up to the collecting area is very short. All in all and trying to be practical, we assume that all the effective rainfall generated by the downpour in the contributing area, will reach the collecting (basin) area as surface runoff. Consequently:

$E_{s1} = S_1 \cdot \int_0^D e(t)\cdot dt$; where E_{s1} is the surface runoff volume produced by the rainfall in the contributing area, which feeds the collecting area. If we wish to express the result in litres per square metre of the collecting area, we should write:

$$E_{s1} = \frac{S_1}{S_2}\cdot \int_0^D e(t)\cdot dt$$

The infiltration generated in the collecting area is more complex to calculate. A continuity equation in the micropond must be established to obtain the runoff volume that escapes from the systematized unit (E_{s2}).

$$\frac{dV}{dt} = I(t) - Q(t)$$

where: $I(t) = i(t) \cdot S_2 + e(t) \cdot S_1$ is the inflow rate;
$Q(t) = w_i(t) \cdot S_2 + F(h)$ is the outflow rate with $w_i(t)$ = infiltration rate in the collecting area and $F(h)$ = outflow through the structure's outlet being a function of the total head on the crest (h).

Therefore, the micropond equation may be written either:

$\frac{dV}{dt} = i(t) \cdot S_2 + e(t) \cdot S_1 - w_i(t) \cdot S_2 - F(h)$ or (MARTÍNEZ DE AZAGRA, 1994):

$$\longrightarrow \quad \boxed{\frac{S(y) \cdot dy}{dt} = i(t) \cdot S_2 + [i(t) - v_i(t)] \cdot S_1 - w_i(t) \cdot S_2 - k \cdot (y - H)^x}$$

where: y is the water (sheet) depth in the micropond, S(y) is the ponding surface and $k \cdot (y-H)^x$ is the discharge equation of the outlet [with k = discharge coefficient, (y - H) = h = total head and x = discharge exponent that is 1.5 for unsubmerged spillover].

It is a differential equation not separable, the integration of which is only possible under particular assumptions. Once it is integrated we can obtain the surface runoff volume that escapes from the systematized unit (E_{s2}) and thus, the system is solved.

$$E_{s2} = \frac{1}{S_2} \cdot \int_0^{D+t_v} F(h) \cdot dt,$$ where t_v is the final overflowing time

$$\longrightarrow \quad \boxed{DESP = P + \frac{S_1}{S_2} \cdot \int_0^{D} e(t) \cdot dt - \frac{1}{S_2} \cdot \int_0^{D+t_v} F(h) \cdot dt}$$

To find out the infiltrated water volume in the collecting area (DESP) the following equation can also be used:

$$\longrightarrow \quad \boxed{DESP = \int_o^{D+t_v} w_i(t) \cdot dt + \frac{V_f - V_i}{S_2}}$$

But in this case yet again, we have to make use of the continuity equation to work out V_f (the accumulated water volume at the end of the precipitation event) and V_i (the initial water volume in the micropond).

3. Characteristic times in the functioning of a micropond

In the initial stages of a precipitation event both the contributing and the collecting area can infiltrate all the rainwater. After a certain time, the ponding time is reached in the contributing area. From this moment on, the system begins to generate runoff towards the collecting area. The rain episode is then profitable for the basin area, which obtains an additional supply of water on top of its own rainwater.

Ponding of the basin area may occur either before or after the arrival of the runoff water yielded by the contributing area. Thus, two ponding times can be distinguished: one, corresponding to the producing area (t_i), which define the moment when the rainfall starts to be efficient to the set up systematization; and a second one corresponding to the collecting area (t_r), which marks the beginning of the micropond filling.

Whenever the infiltration capacity of the catchment area is below that of the basin area, the runoff formation in the former zone will precede the occurrence of the first pools in the latter (for $t_i < t_r$). This situation indicates a greater infiltration capacity of the collecting area, which is advantageous for the aims pursued: water availability of the basin area tends to be bigger than the one in the contributing area, without the need to create a mini-dam.

The working of the micropond is shown with the differential equation stated in the previous section. For a simple rainfall (that is, with only two ponding times: t_i and t_r) greater than the limit precipitation of the systematized unit, we may distinguish four different situations that correspond to an equivalent number of particularizations of the above mentioned differential equation: an initial phase of filling without spillage, a second stage of filling with overflowing, a third phase of emptying out with overflowing after the end of the rainfall, and, finally, a phase of hollowing out without spillage until the infiltration of the stored water has concluded. By marking out each of these stages, there are some characteristic times described below:

$t_0 = 0$; beginning of the rainfall

t_i = ponding time of the contributing area

t_r = ponding time of the collecting area

t_l = limit time for the systematized unit (the moment when E_{s2} starts)

D = rainfall duration

t_v = overflowing final time (interval between the end of the rainfall and the end of the spillage)

t_f = conclusion time (= duration of the infiltration in the micropond)

In Figure 4 we outline the phases in the functioning of a micropond, we indicate the differential equation suitable for each case and we mark the characteristic times. There is a computer program (FUMIC.EXE) developed by J. DEL RÍO and R. FERNÁNDEZ DE VILLARÁN in 1995 that displays all these circumstances (MARTÍNEZ DE AZAGRA, 1996). Obviously, for more complex precipitation events with important variations in rain intensity it may be possible to contemplate intermediate hollowing out and/or filling stages.

The existing differences between the traditional approaches of surface hydrology and those studied in this work are evident and they can be summed up in a simple sentence: what matters in an arid slope ecosystem is not the water that flows away but the one that remains. So, in this case, we emphasize the times prior to the beginning of the overflowing and the total infiltration time, whereas we disregard the characteristic times commonly considered in the (streamflow) hydrograph (the only exception being the base time called here overflowing period and that we intend to nullify by means of the water traps). Thus, we postulate a new field within the realm of Forest Hydrology of arid zones, primarily concerned with vegetation development and keeping its distance from the drainage net.

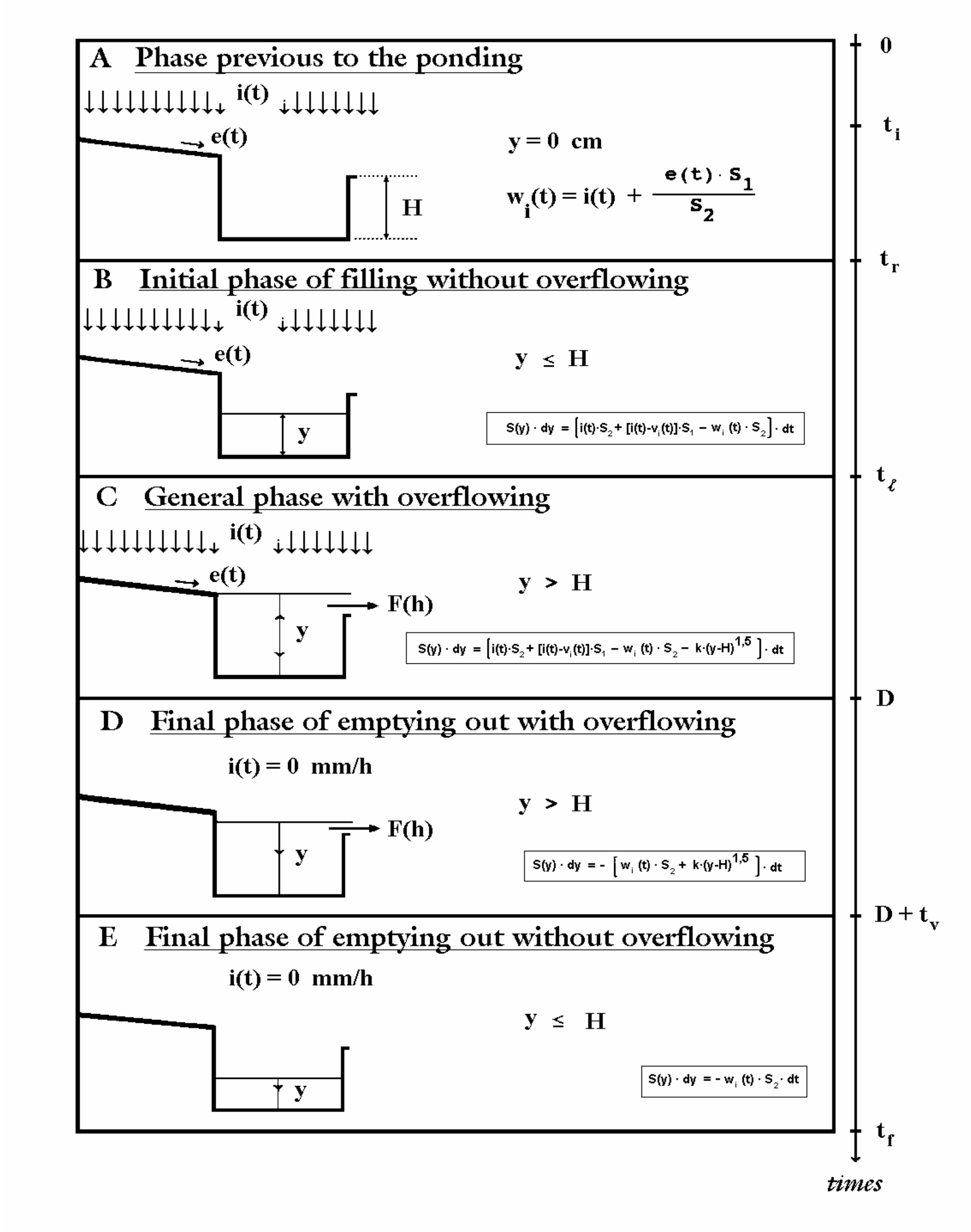

Figure 4: Characteristic times in the functioning of a micropond

4. Particularizations to the general model

The general equations developed in the preceding sections can be specified for different systematizations and rainfalls. There is a large number of cases to be raised and they may be obtained by combining the seven (or eight) input variables within the formulated problem: The runoff surface area (S_1) and the basin area one (S_2) as well as the micropond top capacity ($CAPA \approx S_2 \cdot H$) are constant whereas the rest of the parameters change in time. The infiltration rate of both the producing ($v_i(t)$) and the collecting area ($w_i(t)$), the discharge equation ($F(h)$), and the flooded area of the micropond ($S(y)$) depend on the rainfall intensity ($i(t)$) and they are interrelated by the repeatedly mentioned differential equation.

As the possibilities are almost countless, we will just present a rough sketch. With regard to precipitation it is possible to work either with hyetographs of rainfalls that have really taken place or - on the contrary - with synthetic precipitation with some statistical meaning that is worth analyzing. The easiest particularization consists of working with constant intensity rainfalls ($i(t)=k$).

To characterize the infiltration process in both the producing and the collecting area, different possibilities are likely: from working directly with the experimental data obtained with infiltrometers or with rainfall simulators, to using general simple and semi-calibrated models, such as, for example, the curve number model; or working with constant infiltration rates (e.g. the average infiltration capacity for a determined interval of time). A halfway solution consists of adjusting the achieved experimental values to certain infiltration models (the HORTON, or KOSTIAKOV, or PHILIP model, and so on). With regard to this subject, it is important to state that those models that determine the infiltration capacity according to the time and the previously infiltrated water volume (GREEN-AMPT, or HOLTAN equation, etc.) are not useful for this study, since they require an input datum that is the main unknown quantity we are searching for.

The overflowing of water, when it occurs, follows the discharge equation through a spillway (or outlet). A simplified hypothesis consists in admitting that the excess water spills over instantaneously as soon as the water reaches the top of the spillway, but this underestimates the actual infiltration occurring in the collecting area.

Finally, the ponded surface (or the stored water volume in the micropond) is very easily established provided the water level is horizontal. Knowing the water depth and the microtopography of the collecting area we can solve the question. A simplification that needs to be considered is to suppose that the flooded area is constant and equal to the basin area all the time: $S(y) = \text{constant} = S_2$.

To begin with we have developed two particularizations of the general model: one of them makes use of the curve number method to estimate runoffs and to evaluate infiltrations. It is the easiest methodology to apply. It has been presented in detail through a book which includes a diskette, with the computerized model (MODIPÉ program, MARTÍNEZ DE AZAGRA, 1996).

The second particularization uses the HORTON infiltration model (1940), taking on the MLS (1980), KUTÍLEK (1980) and VERMA (1982) hypotheses to calculate the ponding times. It creates two different infiltration capacity curves to, this way, simulate the effects of the preparation of the soil: an equation for the runoff area [$f(t) = f_c + (f_0 - f_c)\cdot e^{-\alpha\cdot t}$] and another one for the collecting area [$g(t) = g_c + (g_0 - g_c)\cdot e^{-\beta\cdot t}$]. Therefore, and to characterize the infiltration process, this model employs six input parameters [initial infiltration capacity (f_0 and g_0), final infiltration capacity (f_c and g_c) and the decrease exponent (α and β, respectively)] in contrast to the two ones used by MODIPÉ, [namely: the curve numbers of the contributing area (NI) and those of the collecting area (NR)].

This second model (called HYDNUM) works with a rainfall of constant intensity and changeable duration (i(t)=k; D). For such a rainfall, with an intensity comprised between the maximum and minimum water infiltration rates (that is: $f_c < k < f_0$), the ponding time in the producing area (t_i) is obtained by means of this expression:

$$t_i = \frac{1}{\alpha \cdot k} \cdot \left[f_0 - k + f_c \cdot \ln \frac{f_0 - f_c}{k - f_c} \right] \quad \text{(VERMA, 1982)}$$

To know the infiltration rate once the ponding time has been reached, we have to work out a chronological change or a temporal shift (Δt) which is expressed:

$$\Delta \mathrm{t} = \frac{1}{\alpha \cdot k} \cdot \left[f_0 - k + f_c \cdot \ln \frac{f_0 - f_c}{k - f_c} \right] + \frac{1}{\alpha} \cdot \ln \frac{k - f_c}{f_0 - f_c}$$

This difference of time can be physically justified by the fact that the soil filters less water than it is able to at the beginning of the storm (k instead of f_0). And this economy leads to a ponding time which comes later than the deduced one by making equal both the infiltration capacity and the rainfall intensity.

Once calculated Δt, the infiltration rate in the runoff area is:

$$v_i(t) = f_c + (f_0 - f_c) \cdot e^{-\alpha \cdot (t - \Delta t)}$$

then, we can obtain the total water volume infiltrated in the producing area caused by the shower:

$$\text{PIMP} = \int_0^D v_i(t) \cdot dt = \int_0^{t_i} k \cdot dt + \int_{t_i}^{D} \left[f_c + (f_0 - f_c) \cdot e^{-\alpha \cdot (t - \Delta t)} \right] \cdot dt \qquad \Rightarrow$$

$$PIMP = k \cdot t_i + f_c \cdot (D - t_i) + \frac{1}{\alpha} \cdot (f_0 - f_c) \cdot e^{\alpha \cdot \Delta t} \cdot e^{-\alpha \cdot t_i} - \frac{1}{\alpha} \cdot (f_0 - f_c) \cdot e^{\alpha \cdot \Delta t} \cdot e^{-\alpha \cdot D}$$

In a similar way, we can estimate the ponding time in the collecting area (t_r) and the infiltrated water volume (DESP). In this case, the expressions are much more complex. Thus, and to obtain t_r, we have to consider that the basin area is receiving the direct rainwater as well as the runoff from the contributing area (since the instant t_i). The equivalent rainfall intensity will be:

$$i(t) = k + [k - f_c - (f_0 - f_c) \cdot e^{-\alpha \cdot (t - \Delta t)}] \cdot \frac{S_1}{S_2}$$

On the other hand, the differential equation of the micropond may be written like this:

$$S(y) \cdot dy = \left[k \cdot S_2 + \Theta \cdot \left\{ k - f_c - (f_0 - f_c) \cdot e^{-\alpha \cdot (t - \Delta t)} \right\} \cdot S_1 - \left(g_c + (g_0 - g_c) \cdot e^{-\beta \cdot (t - \Phi t)} \right) \cdot S_2 - \Omega \cdot k \cdot h^x \right] \cdot dt$$

where all terms are known except for the operators Θ and Ω and the movement of time Φt, the same concept as the one already seen for the producing area (Δt). The operators can be either zero or one, depending on whether some particular characteristic times have been reached or not. To be exact:

Θ is zero up to $t = t_i$, it is one from this moment on and until t=D, and it turns zero again when the rainfall ends;

Ω is zero until the limit time is not achieved (t_l), one till the moment D+t_v , and it is zero once again from this moment onwards.

This differential equation governs the water stock process and infiltration in the collecting area from the moment when the ponding time of the basin area is reached (t_r), to the conclusion time (t_f), when the infiltration finishes.

To solve the problem, the computer program HYDNUM assumes that the flooded surface (S(y)) coincides with the basin area: $S(y)=S_2$ and also that there is not stored water volume at all in the micropond, when the precipitation starts, that is: y = 0 ($\Leftrightarrow V_i=0$). As a discharge equation, the model makes use of the spillway discharge one:

$$F(h) = k \cdot h^x = c \cdot L \cdot (y-H)^{1,5}$$

in which c is the discharge coefficient and L is the average width of the excess water spillway.

As we can see, these equations do not seem to have a very friendly appearance. The most complicated expressions especially occur when we solve the differential equation of the micropond. So, to obtain the limit time (t_l), a method of successive approximation is required. The final overflowing time (t_v) is not much simpler either, because it demands several mathematical skills. But the solution to the equations of the system in order to define all the characteristic times (t_i, t_r, t_l, t_v y t_f) does not present any conceptual difficulty.

As a comparative summary of the two expounded particularizations (HYDNUM and MODIPÉ), we have devised Table I.

INPUT DATA	HYDNUM PROGRAMME	MODIPÉ PROGRAMME
contributing area	S_1	S_1
collecting area	S_2	S_2
storage capacity of the micropond	H	CAPA
characteristics of the infiltration in the contributing area	f_0 , f_c and α	NI
characteristics of the infiltration in the collecting area	g_0 , g_c and β	NR
water excess discharge equation	$F(h) = c \cdot L \cdot h^{1,5}$	instant spillage
original situation (undisturbed slope)	--------	NAC
Rainfall	$i(t) = k$	1) a single storm 2) a series of rainfalls 3) a year

Table I: Summary of the two particularizations developed by MARTÍNEZ DE AZAGRA (1995)

Finally, we add a practical case solved by means of the HYDNUM program, which can be quite illustrative. It is about a degraded clayey slope in the region of Almazán (Soria, Spain), Once the infiltration tests have been carried out, they have been adjusted to the Horton model by least square. This is the result: f_0 = 94 mm/h; f_c = 5 mm/h; α = 0.05 min^{-1}. The systematized unit surface is 10 m^2 ($\Leftrightarrow$ planting density: 1000 feet/ha). The contributing area is 9 m^2 (where we let soil and vegetation unaltered), the remaining square metre corresponds to the basin area with a mini-dam in which H is 200 mm high (therefore, CAPA = 200 l). Soil manipulation techniques in the plateau have proved to be helpful in improving infiltration, which is evident when we observe the new adjustment parameters to the Horton's infiltration equation: g_0 = 203 mm/h (> f_0); g_c = 5 mm/h (= f_c) and β = 0.04 min^{-1} (<α). The water excess spillage is produced by the sides of the plateau through the two lateral outlets to which we have given a total width (L) of half a metre with a discharge coefficient (c) of 0.3.

For a 20 mm/h intensity downpour, the limit time of the systematized unit reaches 187 min, which is equivalent to a 62.3 l/m^2 precipitation. This prolonged interval of time for the chosen rainfall intensity, gives us a first orientation about the working of the system, which will be endorheic for most of the showers. The rainfall I-D-F curves (rainfall intensity - duration - frequency curves) in the zone, may define the return period of the limit precipitation (62.3 mm) in an accurate way. With a similar criterion we can search for a guarantee of endorheism for some years, a period which should be related to how fast the afforestation develops.

According to the results of the simulation carried out by means of the HYDNUM program, we come to the conclusion that the precipitation is weak for a fifty - minute duration. Water harvesting is not produced. All the rainwater infiltrates where it falls; so: PIMP=DESP=PROM=P= 16.7 l/m^2 , since the ponding time in the contributing area is not achieved: t_i = 83 min.

If we double the rainfall duration (D = 100 minutes) the precipitation is considered effective. It brings about a water harvest of 12.6 litres in the collecting area ($\Rightarrow$ PIMP = 31.9 mm; DESP = 45.9 mm; PROM = P = 33.3 mm). This water harvesting is attained without the need of any mini-dams thanks to a good preparation of the soil in the basin area (t_r =118 min > D, according to the results of the HYDNUM model).

For a rainfall that lasts 150 min (P=50 mm), the precipitation is effective but some mini-dams of 111 mm height are required. With this rainfall, the runoff area contribution (E_{s1}) is 107.5 litres. This way, a great part of the fallen water accumulates and infiltrates in the collecting area: DESP = 157.5 mm in comparison with 38.1 l/m^2 in the contributing area.

If we increase rainfall duration above the limit time (D> t_l = 187 min) the microcatchment will no longer be endorheic. Therefore, a rainfall intensity of 20 mm/h for 200 min is excessive for the systematized unit. In other words: if we expect a complete use of this rainwater in the slope, mini-dams larger than those here designed will be necessary (233 mm instead of 200 mm). Overflowing leads to some average water availability lower than the incidental rainfall: PROM = 65.5 mm in contrast to the 66.7 l/m^2 recorded on a rain gauge. The amount of rainwater that escapes from the systematization is E_{s2} = 32.7 litres. On the other hand, the runoff the micropond receives from the contributing area is 218.6 litres. As a result of these two processes a very unequal distribution of the rainwater is produced: PIMP = 42.4 mm; DESP = 273.7 l/m^2. Finally, it is important to say that, owing to the low final infiltration rates (g_0 = 5 mm/h), the conclusion time is delayed over a day and a half (t_f = 2601 min) which can produce a complete lack of oxygen in the roots of the plants located in the micropond.

5. Conclusions

Water harvesting is an essential strategy for the rehabilitation of degraded slopes in arid zones. Besides the erosive processes that might appear, a simultaneous desertification occurs because of paedological aridity which needs to be altered by means of conveniently sized and distributed water traps (microponds). The low infiltration rates of these slopes can be favourably useful for water retention and infiltration in the collecting areas. This supplementary watering in the key places helps to reduce failures due to water stress at the most critical stages of the establishment and first growth of the seedling.

Management and harvesting of runoff for afforestation purposes must be planned and performed with the greatest care, since accumulating water without any calculations can be dangerous, especially if we work with small reforestation densities (=large unit areas). The risk of increasing the erosive processes through an unplanned intervention is high; the more torrential the climate is, the greater.

As the existing farming models about water harvesting are not applicable to afforestation, a hydrological model, specific for our sector, has been developed. This hydrological model and its two particularizations open a new field in Forest Hydrology, more concerned with the water budget of sloping lands. The two computer programmes originated in a research project (called HYDNUM and MODIPÉ), will allow us to standardize the soil manipulation techniques in accordance to the water availability required by the ecosystem, to achieve some denser and more evolved plant associations.

6. References

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