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Use of GIS and remote sensing in identifying recharge zones in an arid catchment: a case study of Roxo River basin, Portugal

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ABSTRACT

A water balance model for the Roxo catchment in Portugal was developed based on ground data and satellite imageries. The model used the Thornthwaite-Mather method of analysing the recent (2001–2003) climatological records. The amount of annual runoff from the catchment predicted by the model is 29 million m^3, which is accumulated in the Roxo reservoir. Almost all the discharge is contributed by the direct runoff and the groundwater contribution is insignificant. However, there are some groundwater recharge zones in the northern part of the catchment. With the help of remote sensing and geographic information system, it was possible to identify the groundwater recharge zones in an arid region like the Roxo catchment, where the traditional one-point calculation method failed to give any results.

INTRODUCTION

Fresh water is becoming a scarce resource day by day in every part of the world, and Portugal is no exception. The only option left to cope with this situation is to conserve water resources. Since the amount of rainfall and evapotranspiration rate vary within a watershed, water available for surface and groundwater recharge also varies both on spatial and temporal scales. Moreover, groundwater recharge (and ultimately the total water yield) is directly influenced by the soil texture and land cover in the watershed. The soil texture is generally persistent while the land cover widely changes over the years owing to natural calamities, human encroachment, and other anthropogenic activities. Hence, the potential groundwater recharge zones have to be identified and preserved for the purpose of water resources management, particularly in an arid or semi-arid region.

A rainfall-runoff water balance model at a meso level estimates the total catchment runoff produced in a watershed in a monthly time step. Such a model investigates the contribution of surface runoff and groundwater flow to the total catchment runoff. One of such models is based on the Thornthwaite-Mather method, which estimates the groundwater recharge and amount of groundwater flow in the catchment by taking into consideration the water-holding capacity (WHC) of soil. The WHC is characterised by two factors: soil texture and type of vegetation. Therefore, for a successful implementation of the model, it is required to prepare a soil texture map, a land cover map, and then a WHC map. Based on these maps, it is possible to estimate the spatial and temporal distribution of groundwater recharge and groundwater flow in a watershed.

PHYSIOGRAPHY AND HYDROLOGY

The Roxo watershed (37°46′44″ N to 38°02′39″ N latitude and 7°5′47″ E to 8°12′24″ E longitude) with an area of 353 km^2 is located in the Beja district of the Alentejo province of southern Portugal (Fig. 1). The district's population is 161,200, of which 40,000 live in the Beja town. The water produced in the catchment is accumulated in an artificial reservoir covering an average area of 1,378 ha. But the reservoir area varies from season to season. The construction of reservoir dam was started in 1963 and was completed in 1968. The reservoir water is used mainly for irrigation and domestic purposes. It is also used by some local industries.

The Mediterranean climate predominates in the area. Like any other part of southern Portugal, the area is much warmer and receives less rainfall than the national average. The temperature reaches a maximum of 40 °C in summer (i.e., July or August) and a minimum of 5 °C in winter (i.e., December). The mean annual rainfall in the area is estimated to be 550 mm. The period from May to September is very dry. The area is wet from the month of October to April. In average, 85 per cent of the total annual rainfall occurs during this period. The highest amount of rainfall occurs in December, while July and August are the driest months.

The catchment is dominated by rolling plains and arable lands. The altitude of the watershed varies from 123 to 280 m. It is the major food producing region of Portugal. The Alentejo province alone yields 75 per cent of the country's total wheat production. The province is also renowned for its large stands

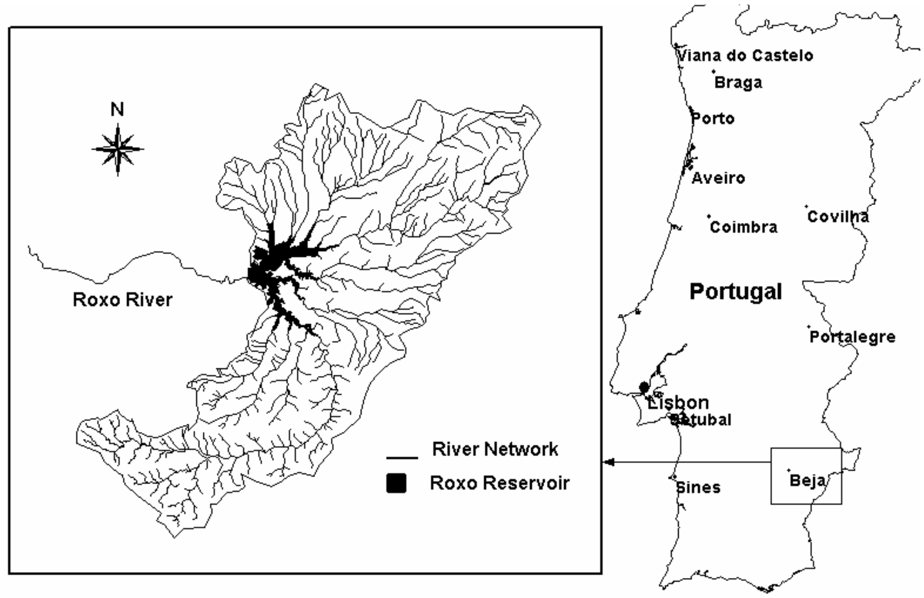

Fig. 1: Location of the Roxo Catchment in the map of Portugal

of cork oaks and olive groves. Irrigation and mechanised agricultural technology are well established in this region.

WATER BALANCE MODEL

A model developed by Thornthwaite and Mather (1955) was applied to develop the rainfall-runoff water balance for the Roxo catchment. Basically, the Thornthwaite-Mather method computes the water balance for one point. But the water balance can be modelled for the entire catchment using GIS techniques. In order to do so, a spatial distribution of rainfall, potential evapotranspiration, soil texture, and rooting depth of land cover in the catchment have to be taken into account. In this study, the Thornthwaite-Mather method was implemented as explained by Dunne and Leopold (1978).

At first, the water balance in the reservoir was obtained from measured data. This balance determines the runoff from the catchment. Based on the catchment runoff, a direct storm runoff coefficient was derived and used subsequently in the water balance estimates for the catchment (Fig. 2). The water balance model simulates a monthly total runoff from the catchment, and thus estimates the total runoff accumulated in the Roxo reservoir.

The model assumes that a certain fixed percentage of rainfall (P) leaves the area as a direct runoff (*DRO*). This percentage is used to obtain the direct storm runoff coefficient (*C1*). The remaining portion of rainfall is called the effective rainfall (P_{eff}).

$$DRO_{(i)} = C1 \times P_{(i)} \quad ....(1)$$

where i = month number.

$$P_{eff\,(i)} = P_{(i)} - DRO_{(i)} \quad ....(2)$$

A portion of P_{eff} is returned to the atmosphere in the form of evapotranspiration. The remaining portion known as the surface recharge (*SRECH*), i.e., the difference of P_{eff} and potential evapotranspiration (ET_p) is available for infiltration into the soil (if $P_{eff} > ET_p$).

$$SRECH_{(i)} = P_{eff\,(i)} - ET_{p(i)} \quad ....(3)$$

When *SRECH* is positive, i.e., P_{eff} is more than *ETp* and the soil is not yet at its *WHC (Water Holding Capacity)*, *SRECH* will be used to fill up the soil moisture (*SM*) and it is defined by the following formula:

$$SM_{(i)} = SM_{(i-1)} + SRECH_{(i)} \quad ....(4)$$

As soon as *SM* reaches *WHC*, the remaining part is available for runoff either as a groundwater runoff or a surface runoff. The above calculation should be started from the first wet month.

When *SRECH* is negative i.e., P_{eff} is less than ET_p, water is withdrawn from *SM*. This results into the exponential soil moisture depletion and is defined by the following formula:

$$SM_{(i)} = WHC \times \exp^{\left[APWL(i) / WHC \right]} \quad ....(5)$$

where *APWL* is the accumulated potential water loss, which is always negative. It is the variable that describes the dryness of soil. For the months with a deficit of water (*SRECH < 0*), *APWL* is calculated as follows:

$$APWL_{(i)} = APWL_{(i-1)} - SRECH_{(i)} \quad ....(6)$$

For the months with a surplus of water (*SRECH > 0*), *APWL* is 0, indicating no dryness in the soil.

If P_{eff} is higher than ET_p, the actual evapotranspiration (ET_a) equals ET_p. If not, it is computed as:

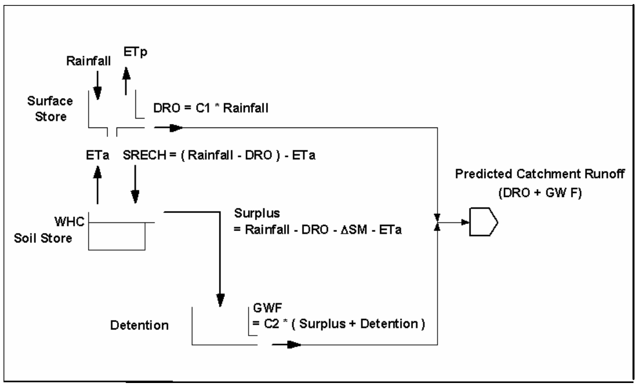

Fig. 2: Graphical representation of the Water Balance Model

$$ET_{a(i)} = P_{eff\,(i)} - \Delta SM_{(i)} \quad (7)$$

where ΔSM is the difference between the soil moisture content in the current and previous months. It is given by:

$$\Delta SM_{(i)} = SM_{(i)} - SM_{(i-1)} \quad (8)$$

The soil moisture deficit is the difference between ET_p and ET_a within the same month, and is given by:

$$Deficit_{(i)} = ET_{p(i)} - ET_{a(i)} \quad (9)$$

The soil moisture surplus is the difference between the effective rainfall and the sum of ΔSM and ET_a. It is the excess rainfall when the soil layer under consideration is saturated with water.

$$Surplus_{(i)} = P_{eff\,(i)} - [\Delta SM_{(i)} + ET_{a(i)}] \quad (10)$$

The surplus water percolates in a soil layer and is added to a detention. The total surplus water of a current month and the detention from the previous month constitute the total available water for subsurface runoff (*TARO*).

$$TARO_{(i)} = Surplus_{(i)} + Detention_{(i-1)} \quad (11)$$

The subsurface storage (or *TARO*) acts as a buffer and causes a delay in groundwater flow (*GWF*). Therefore, not all the water in the storage will become part of *GWF* in the same month. Only a certain fixed percentage of it will be *GWF*, and the remaining part will be detained till the next month. *GWF* is assumed to be 50 per cent (*C2*) of *TARO*. Another 50 per cent remains in the soil as a detention (Dunne and Leopold 1978). A detention of a previous month is available for a surplus of a current month and so on. Finally, the summation of a direct storm runoff (DRO) and a groundwater flow (GWF) in a month gives the total catchment runoff of that month.

$$CatchmentRunoff_{(i)} = DRO_{(i)} + GWF_{(i)} \quad (12)$$

Since the catchment runoff is supposed to be accumulated in the Roxo reservoir, inflow to the reservoir from the catchment would be equal to the catchment runoff.

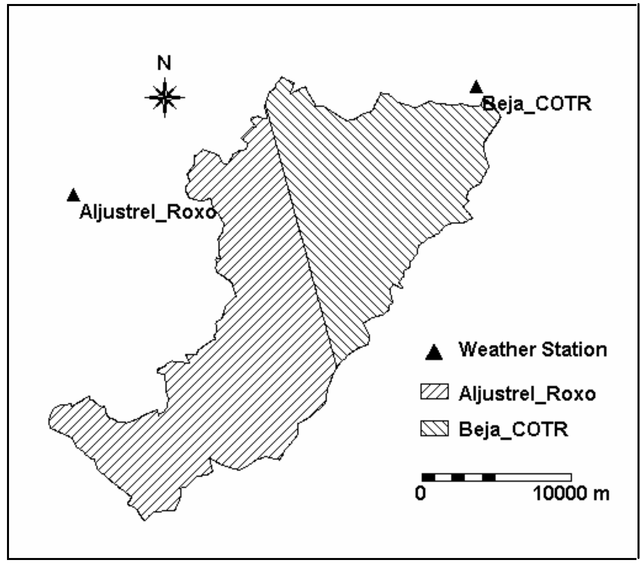

Fig. 3: Sub-regions in the catchment area assigned to the weather stations

SPATIAL AND TEMPORAL DISTRIBUTION OF RAINFALL AND ET_P

The rainfall data from 2001 to 2003 were collected from the two automatic weather stations located, respectively, at the office of Centro Operative de Technological de Regadio (COTR) in Beja and in Aljustrel (Fig. 3). These weather stations were selected due to their close proximity to the catchment area. Even though long-term rainfall data were available from other four manually operated rain-gauge stations, they were not used in the water balance model due to their unreliability. The annual mean rainfall based on these manually-operated rain gauge stations was around 550 mm, while the automatic weather stations estimated the annual rainfall at 600 mm (Table 1). Moreover, the rainfall difference in a monthly time step was very high. This difference had a significant influence on the actual monthly evapotranspiration. In addition to it, the ET_P data were available for the time period from 2001 to 2003 from the same automatic weather stations. Therefore, it was decided to use the data from the automatic weather stations only. The Thiessen polygon (or point interpolation) method was used to determine spatial and temporal distributions of rainfall in the catchment using the GIS software ILWIS. In this method, every sub-region is assigned to a rainfall value of corresponding month measured at its representative climatological station. The sub-regions are defined in such a way that all points in each sub-region are closer to their representative station than they are to any other station.

In this study, the catchment area was divided into two sub-regions approximately centred on each of the two automatic weather stations. Then, the rainfall values representing the sub-regions were assigned. A spatial average of rainfall (*P*) for a certain month is given by:

Table 1: Records of average monthly rainfall (in mm) based on 2001-2003 data at two weather stations

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Aljustrel (Roxo)	44.7	40.3	62.9	85.9	13.6	3.3	1.4	0.4	54.2	99.3	74.6	77.7	558.3
Beja (COTR)	61.6	40.0	76.4	83.9	18.7	5.0	1.7	2.0	68.6	122.7	78.0	82.7	641.3

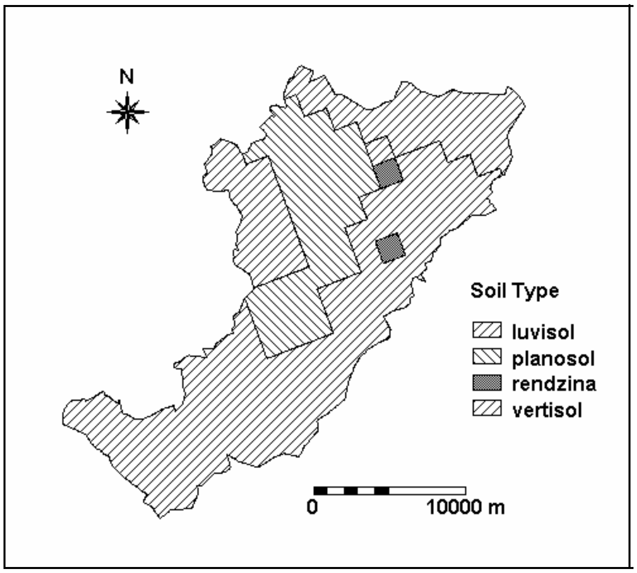

Fig. 4: Soil type map of the catchment

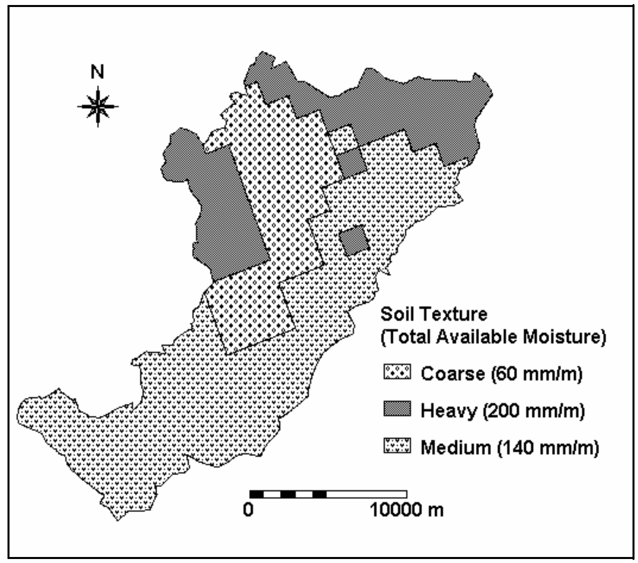

Fig. 5: Soil texture map of the catchment

$$P = \frac{1}{A}\sum_{g=1}^{2} a_g . p_g \qquad (13)$$

where P is the spatial average of rainfall, A is the total area of the catchment, a_g is the area covered by g^{th} station in the catchment, and p_g is the value of rainfall measured at the g^{th} station in a certain month.

The analysis of rainfall trend shows that a high amount of rainfall during the wet season is recorded at the Beja station in comparison with the Aljustrel station.

Similarly, the ET_p data in the daily and monthly time steps were obtained from the same weather stations (Table 2). ET_p was calculated using the Penman-Monteith evapotranspiration method. As in the rainfall, spatial and temporal distributions of ET_p for the catchment area were created using the Thiessen polygon method.

SOIL TYPE AND MOISTURE CONTENT

According to the soil map of Europe prepared by the European Environmental Agency, the soil types of luvisol, planosol, vertisol, and rendzina are present in the catchment (Fig. 4). The planosol has a coarse texture that can hold a soil moisture of 60 mm/m (Fig. 5). The luvisol, which is a major soil type in the area, extends from north to south. It is a deep, loamy soil with a total available soil moisture (TAM) of 140 mm/m. The vertisol and rendzina occupy the northern and north-western parts of the catchment. They are deep, clay-rich soils, and can hold moisture up to 200 mm/m (Doorenbos and Kassam 1986).

LAND COVER AND ROOT DEPTH

A land cover map of the study area was created based on the 8 October 2003 LandSat image using the GIS software ILWIS. Sample points (GPS ground truths) were collected during the fieldwork. The quality of output was verified against the sample points using a number of image classification methods. A comparison of thus obtained land cover class with a random matrix showed that the overall accuracy was 94 per cent. Subsequently, the root-depth values were assigned to every type of land cover (Fig. 6).

The root depth of vegetation in a watershed is directly related to the amount of water available in the soil. Different species of vegetation send roots down into the soil to different depths (Table 3). Cultivated crops such as paddy, tomato, and sunflower are very shallow-rooted (0.25 to 0.30 m), and the amount of water that can be stored in the soil under these crops is small. On the other hand, perennial vegetation like eucalyptus trees, cork trees, and olive trees are deeper rooted (1.5 to 2.0 m) and the amount of water held in their root zone is much larger.

Table 2: Average ET_p values (Based on 2001–2003 data) by month

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Aljustrel (Roxo)	38.7	47.5	78.4	102.1	156.1	183.7	204.3	189.9	127.0	75.4	43.9	31.3	1278.1
Beja (COTR)	39.0	49.4	84.2	105.8	166.2	191.3	221.6	205.4	136.9	78.1	44.5	30.4	1352.5

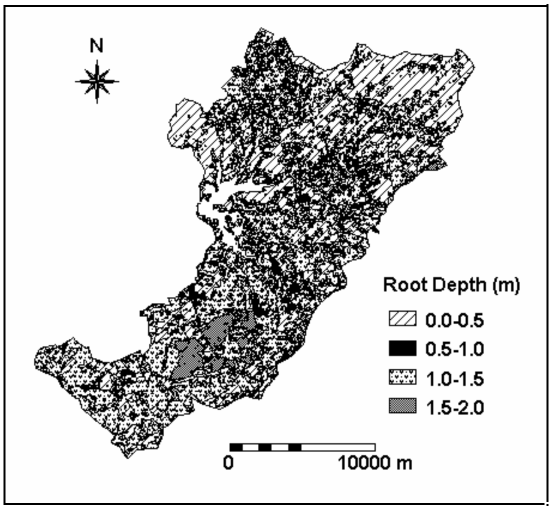

Fig. 6: Root depth map of the catchment

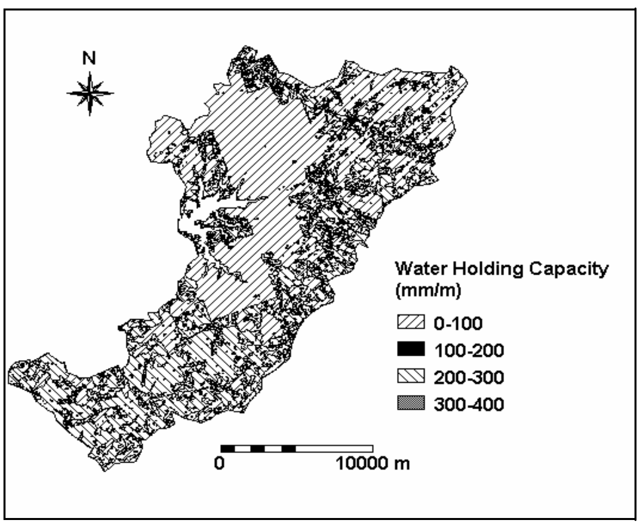

Fig. 7: Water holding capacity map of the catchment

WATER HOLDING CAPACITY

The WHC of soil depends on soil texture and type of vegetation grown on the surface. Different soil textures have different capacity to hold water per unit depth (TAM). At the same time, different vegetation types have different root depths where water can be stored. Hence, WHC in the area can be determined by multiplying TAM of the soil by corresponding root depth of the vegetation grown over there (Fig. 7).

Table 3: Root depth by vegetation type

Vegetation	Root Depth (m)	Vegetation	Root Depth (m)
Apple	1.00	Paddy	0.30
Bare field	0.00	Pine tree	1.50
Barley	0.30	Ploughed field	0.00
Cotton	0.40	Stone or pitch	0.00
Dry grass	0.15	Sugarbeet	0.30
Eucalyptus tree	2.00	Sunflower	0.30
Fodder plant	0.80	Tomato	0.25
Maize	0.40	Urban area	0.00
Melon	0.30	Vine	0.70
Millet	0.30	Water	0.00
Olive/cork	1.50	Wheat	0.30

WATER BALANCE FOR THE CATCHMENT

The computation of water balance components was performed for every pixel inside the catchment boundary excluding the area of the Roxo reservoir and other water bodies. The spatial distribution of the components was obtained in the form of maps. At the end, their average values for the entire catchment (excluding water bodies) were calculated (Table 4).

Direct runoff, groundwater flow, and total runoff from the catchment (except the water bodies) in the monthly time step were the major outputs of the model. In the computation of direct runoff, a direct storm runoff coefficient was assumed at 14 per cent for all the months. This value was determined by comparing the catchment runoff values predicted by the reservoir model and catchment model (Sen 2004). While computing the groundwater flow, it was assumed that 50 per cent of the total available water for runoff (TARO) in any month would actually be the runoff. Remaining 50 percent was supposed to be detained in the subsoil, groundwater, small lakes, and channels of the catchment, which would produce GWF during the next month (Dunne and Leopold 1978). Finally, the total runoff from the catchment was predicted by summing up the direct runoff and GWF in a monthly time step. Simulated values predicted by the water balance model for the entire catchment along with average rainfall (P) and actual evapotranspiration (ET_a) over the catchment area are displayed in Table 4.

The model predicted 85 mm of yearly runoff from the catchment, which makes about 29 million m^3 of annual water yield. The simulated inflow has no consistent trend with respect to monthly time step. It is obvious that the months that receive higher rainfall will produce higher amount of runoff and vice versa. Most significantly, the model depicts that there is a very little groundwater flow from the catchment.

Table 4: Simulated output values for the entire catchment (Land Part) by month (in mm)

Month	P	DRO	ETp	SRECH	APWL	SM	DSM	ETa	Deficit	Surplus	TARO	GWL	DET	TRO
Jan	53	7.3	39	6.2	0	90.4	41.0	27.5	11.4	0.5	1.6	0	0	7.3
Feb	40	5.6	48	-13.8	-13.8	94.8	4.4	38.7	9.7	0	1	0	0	5.6
Mar	70	9.7	81	-21.7	-35.5	82.6	-12.2	71.5	9.5	0	0	0	0	9.7
Apr	85	11.9	104	-30.7	-66.1	69.6	-13.0	86.1	17.7	0	0	0	0	11.9
May	16	2.2	161	-147.0	-213.1	33.9	-35.8	49.5	111.2	0	0	0	0	2.2
Jun	4	0.6	187	-183.7	-396.8	15.2	-18.7	22.1	165.1	0	0	0	0	0.6
Jul	2	0.2	212	-210.8	-607.6	6.4	-8.8	10.2	202.0	0	0	0	0	0.2
Aug	1	0.2	197	-196.0	-803.6	2.9	-3.5	4.4	192.5	0	0	0	0	0.2
Sep	61	8.5	132	-79.3	-882.9	2.1	-0.8	53.0	78.5	0	0	0	0	8.5
Oct	111	15.4	77	17.9	0	14.0	11.9	76.6	0	1.1	1.1	0	0	15.4
Nov	76	10.6	44	21.4	0	28.1	14.1	44.2	0	1.2	1.2	0	0	10.6
Dec	80	11.2	31	37.9	0	49.3	21.2	30.9	0	2.2	2.2	1.1	1.1	12.3
Year	599	83.4	1313	-799.6				514.7				1.1		84.5

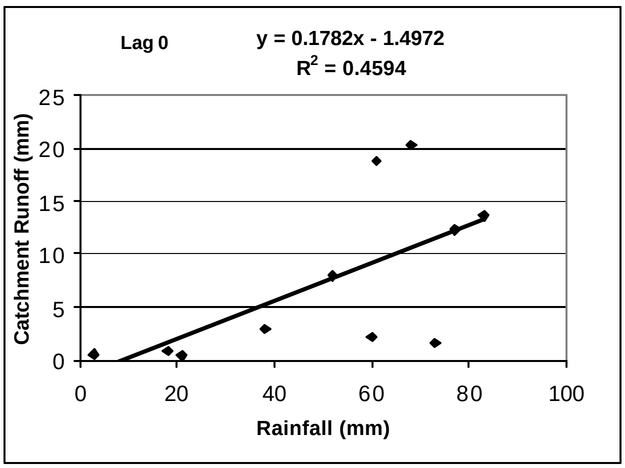

Fig. 8: Regression between rainfall and catchment runoff (measured) in lag 0

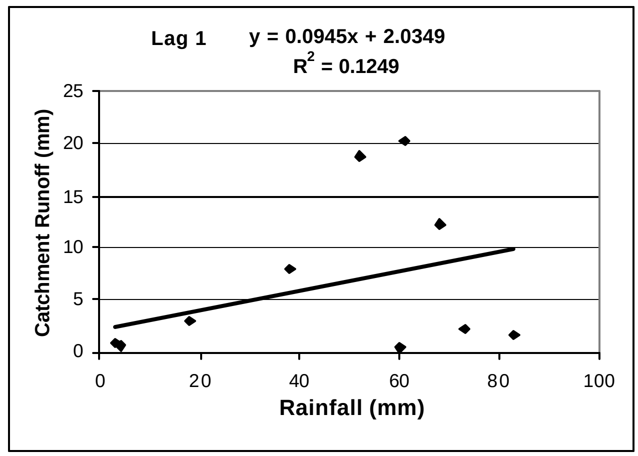

Fig. 9: Regression between rainfall and catchment runoff (measured) in lag 1

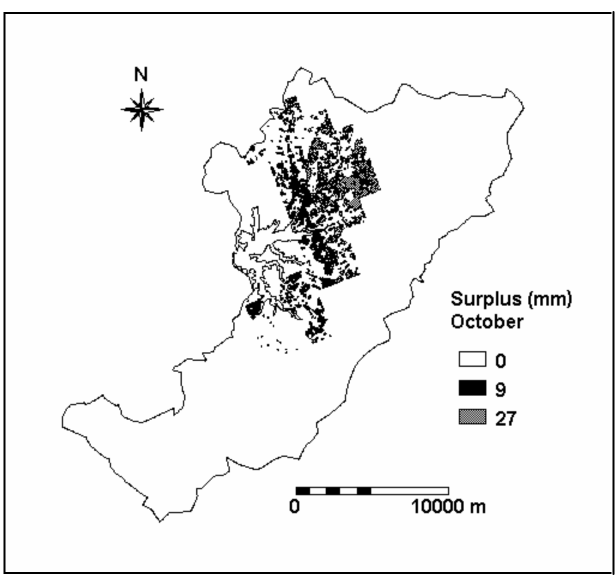

Fig. 10: Surplus water available for groundwater flow in October

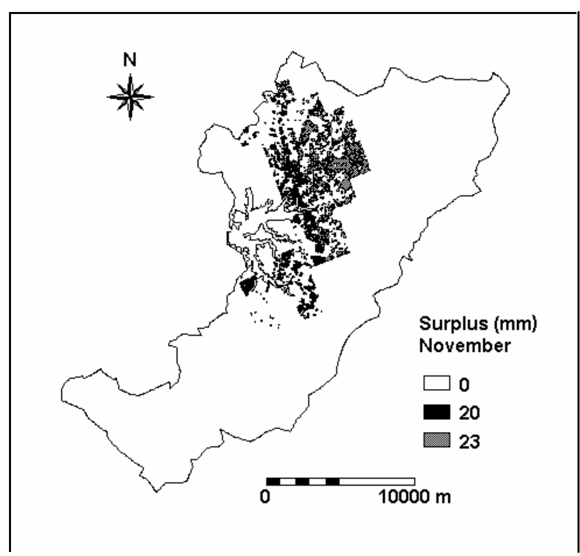

Fig. 11: Surplus water available for groundwater flow in November

The natural precipitation hardly replenishes the soil beyond its WHC. Soil is mainly dry throughout the year. Hence, water drains to the reservoir from the catchment as the surface runoff only. Therefore, the amount of rainfall determines the catchment runoff. In order to validate this idea, a regression analysis was carried out between the rainfall data and the measured catchment runoff taking lag 0 and lag 1 (Fig. 8, and 9). The coefficient of determination was found to be higher for lag 0 than for lag 1. It means that the rainfall occurring in a given month produces the runoff in the same month. The rainfall from the previous month has no or insignificant role in the runoff of the following month. This explains that there is little groundwater detention.

The model shows that the highest amount (15 mm) of runoff takes place in October (Fig. 10). The highest amount (111 mm) of rainfall also occurs in October. During the dry season (May to September), the catchment runoff is also very low. Since only the direct runoff has a contribution to the catchment runoff, negative value in surface recharge (P – DRO – ET_p) has no impact on the total runoff because there is no GWF. Therefore, the amount of rainfall is the only factor that influences the amount of runoff in the Roxo catchment. For instance, in March, April, and September, the total runoff from the catchment is high despite the low effective rainfall with respect to ETp. It is due to the high rainfall in these months. Therefore, the evapotranspiration has no influence in the runoff in this catchment.

There is almost no groundwater flow when the entire catchment is considered as an analysis unit. But, the maps depict some groundwater flow in the northern part of the catchment. Some previous researchers also have argued that there was a groundwater flow in the northern part of the Roxo catchment (also known as the Pisoes sub-catchment), from where it flows towards the reservoir in E-W direction (Paralta 2000).

GROUNDWATER RECHARGE ZONES

In the Roxo catchment, the surplus water is not available between February and September, and there is no groundwater recharge during these months. These are the months when the rainfall is lower than the potential evapotranspiration. From October to January, some groundwater recharge takes place in the northern part of the catchment, which can be considered to be the groundwater recharge zones.

The catchment has a very low groundwater recharge potential. Its recharge area varies from 3 to 6 per cent of the total catchment area in different months. The temporal variation of recharge ranges from 9 mm in October to 41 mm in December. The amount of water available for the groundwater recharge is not the same even during a month. In October, the recharge varies from 9 mm to 27 mm (Fig. 10); in November, it is between 20 mm and 23 mm (Fig. 11), while in December, it reaches the highest value of 36 to 41 mm (Fig. 12). The lowest recharge value of 14 mm is observed in January (Fig. 13).

The groundwater recharge zone (which constitutes a small portion of the total catchment area) is dominantly covered by planosol. This is the soil with a coarse texture and can hold 60 mm/m of water. Hence, the root zone of vegetation intercepts a very little amount of water in this soil.

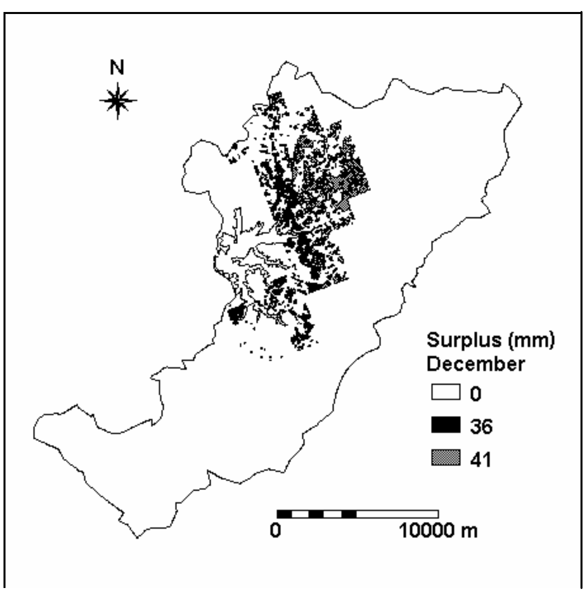

Fig. 12: Surplus water available for groundwater flow in December

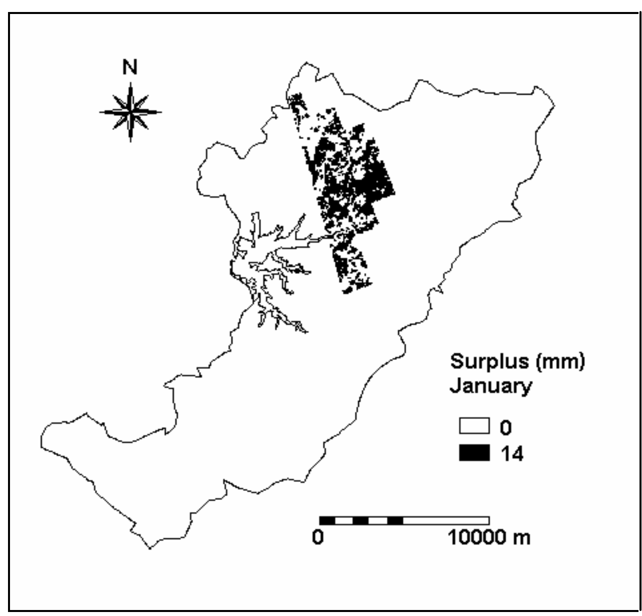

Fig. 13: Surplus water available for groundwater flow in January

CONCLUSIONS AND DISCUSSIONS

With the help of GIS and remote sensing, it was possible to determine the groundwater recharge zones in an arid region like the Roxo catchment, where it was not possible to apply a traditional one-point calculation method. The water balance model shows that the annual runoff from the catchment to the Roxo reservoir is 29 million m^3. The contribution of groundwater flow to the total runoff is very low. The region is very dry and the rainfall is so little that it rarely replenishes the soil moisture to its water-holding capacity. Therefore, the total runoff from the catchment depends primarily on the direct runoff. However, there is some surplus water, which recharges the groundwater in the northern part of the catchment.

The crops as well as large and dense eucalyptus forests in the upstream of the Roxo reservoir undoubtedly withdraw water and thus reduce the runoff to the reservoir. Hence, clearing of the eucalyptus forest and other scrub vegetation in the upstream part can increase water yield from the catchment. As the watershed is gently sloping, the probability of sedimentation in downstream areas due to mass wasting and erosion is very low. Therefore, cutting down the trees on a rotational basis can produce timber and more water in the reservoir.

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