Nordic Hydrology 5, 1974, 229–246
Published by Munksgaard, Copenhagen, Denmark

PROCEDURES FOR EVALUATING THE SURFACE WATER BALANCE OF GRAN CANARIA

LEIF E. AHLGREN and HUBERTUS J. VAN DER ZEL

UNDP, Las Palmas de Gran Canaria, Spain

To evaluate the surface water balance in Gran Canaria, standard procedures were modified to fit local conditions, taking into account the availability and quality of data as well as the special features of the island. In a bookkeeping method the terms of the balance equation were calculated on a daily basis. The precipitation was based on data from a limited number of representative stations. Runoff data were extrapolated by quantifying the characteristics of the geological formations using the SCS curve number method. Potential evapotranspiration data based on Class A pan measurements or Penman calculations were extrapolated using the Blaney-Criddle method, and the real evapotranspiration was calculated using the Thornthwaite-Mather hypothesis. The results of this simplified procedure coincide well with results of an independent evaluation of the recharge.

Gran Canaria is a volcanic island in the Atlantic Ocean, about 200 km off the African west coast at about latitude 28°N and longitude 16°W. Its climate could be described as subtropical with a dry summer. The main factors influencing the climate of the island are its location in the trade wind belt and the surrounding sea.

The island of 1558 km² has an approximately circular shape with diameter 45 km, and a peak of 1947 m in the center of the island. The drainage net is formed principally by radially flowing rivers with steep gradients. The drainage density is low, 1,7 km/km^2, indicating that the island has highly permeable subsoil materials.

In this island the ground water table has dropped so far that nowadays there are no perennial rivers. Runoff occurs only as a result of heavy rains caused by a disturbance of the normal atmospheric conditions, which may happen a couple of times a year and during which all the surface water resources have to be collected. Abundant rainfall data of varying quality, some climatological data and very little streamflow data have been available. The availability of data together with the nature of the precipitation and the different climatological, geological and hydrogeological characteristics of the various parts of the island have influenced the choice of methods used for evaluating the surface water balance.

Elements of the water balance

In order to distinguish the different hydrological and hydrogeological features existing in Gran Canaria, at an early stage of the investigations the island, was divided into nine hydrological zones, some of which in turn were divided into subzones in order to study special drainage basins. Because of the large variations of rainfall and other climatological factors of the zones, these were often divided into smaller units with more uniform conditions in order to increase the accuracy of the balance, since it was decided to assess the water balance for each of these units and summarize the results in a water balance for the island. For the purpose of the water balance the island has been divided into 36 units, the distribution of which is shown in Fig. 1.

The terms considered in the surface-water balance are defined in Fig. 2. With these notations the surface-water balance equation for the unit in natural conditions is:

$$P + Qi = ET + R + Qo \pm \triangle H; \quad (1)$$

with the following relationships between the terms:

$$P = ET + Qp + Rp \pm \triangle H; \quad (2)$$

$$R = Rp + Rq; \quad (3)$$

$$Qo = Qi + Qp - Rq; \quad (4)$$

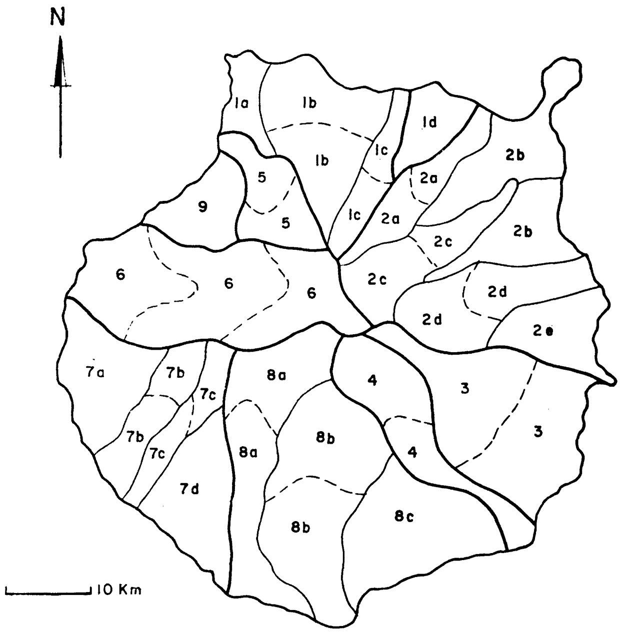

Fig. 1.
Division in hydrological zones.

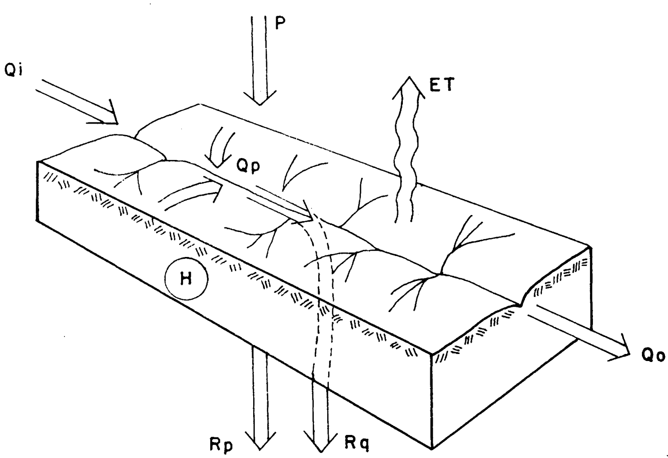

Fig. 2.
The unit used for the surface water balance.

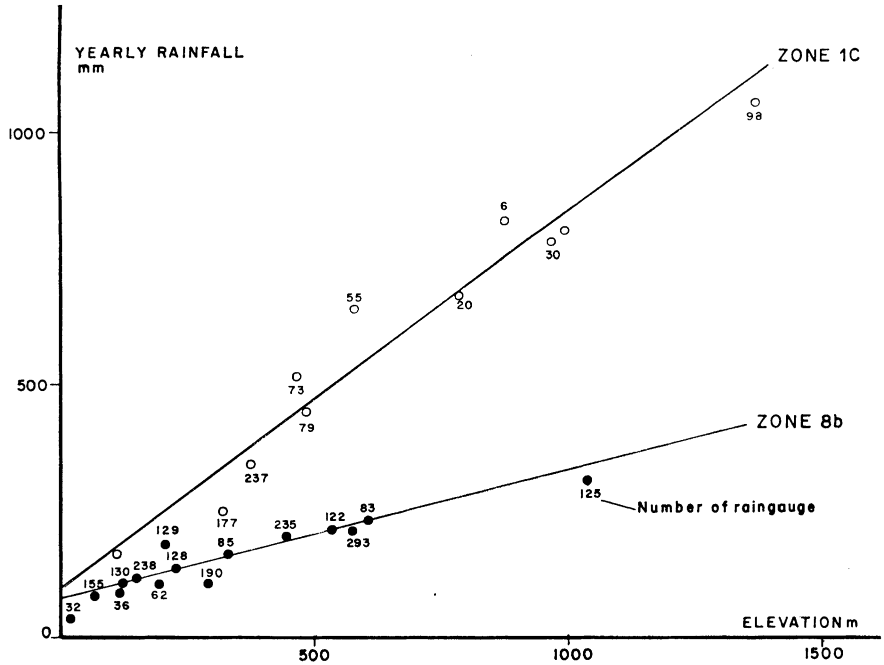

Fig. 3.
Relationship between annual rainfall (1971/72) and elevation.

in which

P ≡ Precipitation
Qi = Surface inflow
Qp = Runoff resulting from precipitation on the unit
Qo = Surface outflow
ET = Evapotranspiration
Rp ≡ Recharge from precipitation
Rq = Recharge from stream percolation
R ≡ Total recharge
△ H = Change in soil moisture storage

The limitation "in natural conditions" means that as a first step in the evaluation, all direct manipulation of water has been disregarded. Artifacts will later be superimposed on the water balance.

Because of the relationship between rainfall and runoff in the Canaries, where often even long periods of rainfall do not provoke any runoff, runoff occurring only as a result of heavy rainstorms, an evaluation of the runoff based on monthly and yearly figures will be very poor. Therefore it is necessary to evaluate these terms on a daily basis in order to obtain values reasonably close to reality. The determination of the daily values of runoff and recharge from precipitation will be made according to the procedures outlined below, after which the effects of stream percolation will be assessed and superimposed according to equations (3) and (4).

It was decided to evaluate the water balance for the three hydrologic years 1970/71, 1971/72 and 1972/73, since for those years some measured streamflow data were available and a simultaneous study of the ground water resources permitted a verification of the results of the surface water balance.

The hydrologic year is defined as the period September 1 to August 31 the following year, which period due to the pronounced seasonal variations of rainfall will minimize the amount of water in transit between two hydrological years.

Precipitation

The existing rain gauge network in Gran Canaria comprises about 270 stations, which gives the very high density of 1 rain gauge per 6 km^2. Many stations, however, are of poor quality and the published records show many irregularities and therefore should be disregarded. For a calculation of the daily rainfall also, it was not practical to utilize all the stations since no computer was available.

It was noticed that because of the orographic effect there exists a linear relationship between rainfall and elevation for the various parts of the island (Fig. 3). This relationship makes it acceptable to use the rainfall at the median elevation of the studied area instead of the Thiessen or Isohyetal method using more stations. Therefore,, in order to simplify the calculation of daily rainfall on the studied area, one or two representative stations were selected and the rainfall for the total area was assumed to be equal to that of the representative stations. These were selected in such a way that their elevations were as close as possible to the median elevation for the studied area, which was obtained from the hypsometric curve.

In order to determine the average rainfall of the island an isohyetal map for the period 1967/68–1971/72 was prepared (Fig. 4). The map was based on the records of 173 stations of reasonably good quality and showed an average rainfall of 350 mm over the island. A standard analysis based on the evaluation of long-term records showed that this period had a rainfall which was about 15 % higher than the median rainfall. Median rainfall for Gran Canaria was therefore estimated at 300 mm.

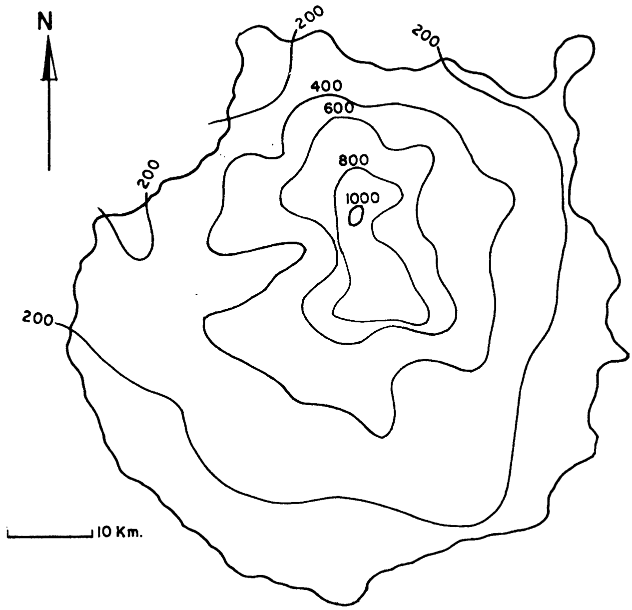

Fig. 4.
Isohyetal map for the period 1967/68–1971/72.

Runoff

Runoff measurements were started in the hydrologic year 1970/71 and are presently carried out at 13 stations in eight pilot basins covering about 15 % of the total area of the island and on which about 30 % of the total precipitation falls. Most rivers have runoff only for a few days a year. After a storm the recession process is very rapid and generally will not take more than a week. Because of these conditions, few spot measurements have been taken and rating curves are based on few data. The many small diversion dams that take out part of the flow during storms are another source of error in the runoff figures.

Due to the relatively small number of recorded storms it was not possible to establish good individual relationships between rainfall and runoff, which are specific for the gauged basins. Instead it was attempted to express the data using the Curve Number method, for which type curves have been published by the US Soil Conservation Service (1957), as shown in Fig. 5. This method is particularly appropriate in this context since it is intended for calculating storm runoff, which is the only type of runoff that occurs in Gran Canaria.

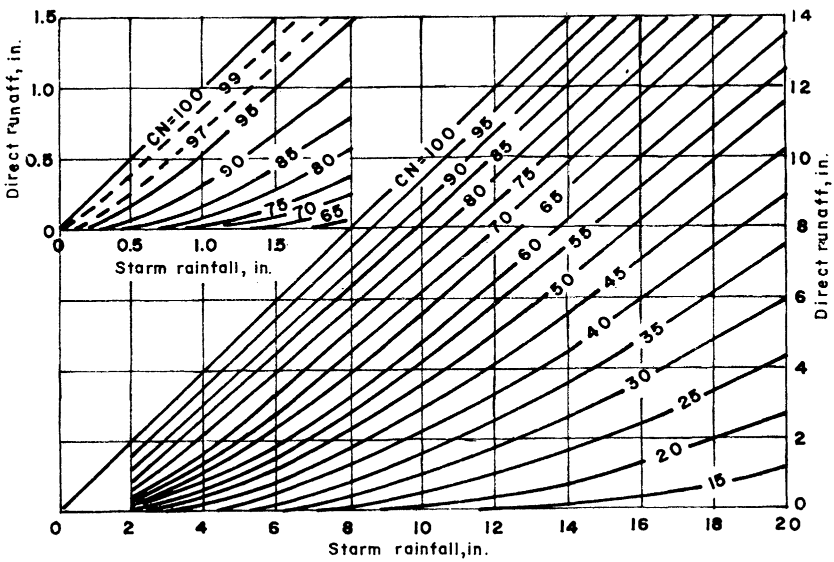

Fig. 5.

Chart for estimating direct runoff according to the curve number method. (From Ven te Chow (1964)).

The relationship can be expressed by the following equations:

$$Q = \frac{(P-0.2\ S)^2}{P+0.8\ S} \tag{5}$$

$$CN = \frac{1000}{S+10} \tag{6}$$

where

Q = Storm runoff, inches

P = Storm rainfall, inches

S ≡ Potential infiltration capacity, inches

CN = Curve number, varying between 0 and 100

For each of the gauged basins, daily rainfall was calculated according to the Thiessen method for each period when there was flow at the stations. The curve number for each storm was found with the graph of Fig. 5. The weighted aver-

Table 1.
Calculation of runoff characteristics for two drainage basins in Gran Canaria.

Date of storm	Measured runoff ≡ Q (mm)	Resulting		Q × S	Calculated runoff (CN = 56) (mm)	Difference (mm)
		CN	S (mm)			
Guiniguada (zone 2 high)						
27/12–'70	26	59	176	4 576	22	–4
11/2 –'71	43	55	208	11 024	54	+1
5/2 –'72	5	47	285	1 425	10	+5
22/2 –'72	3	65	137	411	1	–2
17/12–'73	4	53	225	900	7	–2
Total or average	91	56	201	18 336	94	+3

Date of storm	Measured runoff ≡ Q (mm)	Resulting		Q × S	Calculated runoff (CN = 56) (mm)	Difference (mm)
		CN	S (mm)			
Rosiana (zone 4 high)						
19/11–'71	3	70	109	327	8	+5
23/11–'71	9	81	60	540	7	–2
5/2 –'72	42	77	76	3 192	42	0
22/2 –'72	28	78	72	2 016	27	–1
17/12–'72	62	78	72	4 464	60	–2
7/2 –'73	7	65	137	959	17	+10
12/2 –'73	2	85	45	90	1	–1
Total or average	153	77	76	11 588	162	+9

age curve number of all storms at the stations was calculated based on the potential infiltration capacity, since this parameter can be expressed in a linear unit which has a direct physical meaning in the basin. Two examples are shown in Table 1. The great advantage of this method is that the rainfall-runoff relationship can be expressed in one figure which can be related to other basin characteristics, and thus form a base for the extension of the runoff records to ungauged areas.

Noticing the sometimes considerable differences in runoff characteristics between the various drainage basins and the fact that the curve numbers are lower in the northern part, where the geological formations are predominantly the modern basalts, than in the southern part where phonolites, trachy-syenites and ancient basalts are abundant, we attempted to find a relationship between runoff characteristics and geology. This procedure would provide an objective method for assessing the runoff characteristics of ungauged areas.

The percentages of occurrence of the main geological formations (percentages of the total area of the basin) were related to the infiltration capacity of the basin. Solving an equation system with five unknowns and a few redundant equations for a final check on the results gave values for the potential infiltration capacity of the geological formations within the gauged basins.

Table 2.
Potential infiltration capacity for the main geological formations in Gran Canaria and their equivalent curve number.

Geological formation	Potential infiltration capacity mm	Equivalent curve number	Observations
Ancient basalts	50	84	Estimated
Phonolites, ignimbrites and the Trachy-syenite complex	22	92	
Roque Nublo agglomerates	91	74	
Lower Roque Nublo	151	63	
Modern basalts, lavaflows	265	49	
Modern basalts, pyroclasts	175	59	Estimated
Alluvial materials	200–300	56–46	Estimated
Miocene sediments	75	77	Adjusted

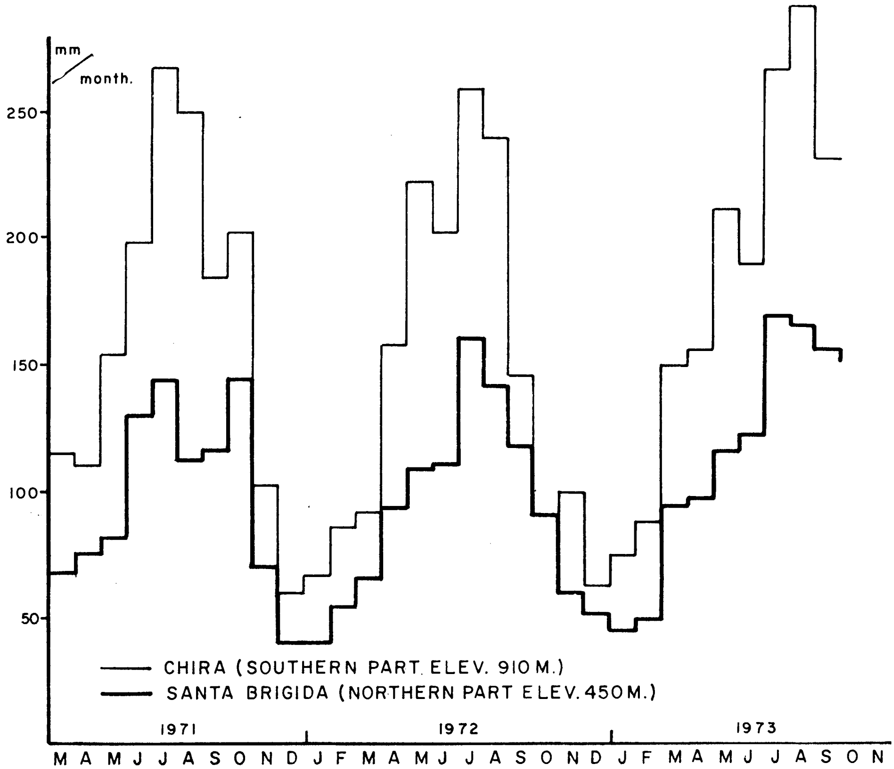

Fig. 6.
Class A pan evaporation for two stations in Gran Canaria.

For those formations where no field data were available or the result did not seem compatible with known hydrogeological characteristics, potential infiltration capacities were estimated taking into account hydrogeological factors (Table 2).

In order to calculate the runoff for each zone in the surface water balance, the weighted value of the potential infiltration capacity for the zone was calculated and the resulting curve number was found from equation (6). Daily runoff could then be calculated assuming the daily rainfall of the representative station to be the storm rainfall.

Potential evapotranspiration

The calculation of the potential evapotranspiration was based on three stations having a U.S. Weather Bureau Class A pan, and three stations that had all data necessary for using the Penman formula. By using a coefficient of 0.75 for both methods, monthly potential evapotranspiration was calculated for the six stations. The evaporation varies considerably between the months and between the northern and southern parts of the island, as can be seen in Fig. 6.

In order to determine the potential evapotranspiration for the whole island, the results from these stations had to be extrapolated to areas with different climatological characteristics.

The only meteorological parameter that is measured reasonably well all over the island is temperature (daily minimum and maximum). It is measured at 25 stations, most of them in the northern and central parts of the island.

The commonly used methods for estimating potential evapotranspiration using only temperature data are those of Thornthwaite and Blaney-Criddle. In order to evaluate these two methods, the potential evapotranspiration was calculated for the six main stations mentioned above. The Blaney-Criddle method gave results that were much closer to the results obtained with the Penman formula and the Class A pan than the Thornthwaite method. Extrapolation of the potential evapotranspiration was therefore done by comparing the Blaney-Criddle method with the Penman calculation or the Class A pan, as the case might be, for the six main stations to obtain for each month of the balance period a modified consumptive use coefficient, F, which will for each station contain all the climatological factors that have influenced evaporation according to the following formula:

$$F = \frac{0.75 \text{ E (pan or Penman)}}{\text{k p } (0.46 \text{ t} + 8.1)} \; ; \qquad (7)$$

where

F = modified consumptive use coefficient
E = measured or calculated evaporation in mm
k = consumptive use coefficient, in this case k = 1
p = monthly percentage of yearly sunshine hours
t = temperature in °C

For the calculation of the potential evapotranspiration the Blaney-Criddle method was used for each of the 36 studied areas, together with the F-value calculated for the closest main station which has similar climatological characteristics, according to the following formula:

$$\text{ETp} = \text{F.p } (0.46 \text{ t} + 8.1); \qquad (8)$$

where

ETp = potential evapotranspiration in mm

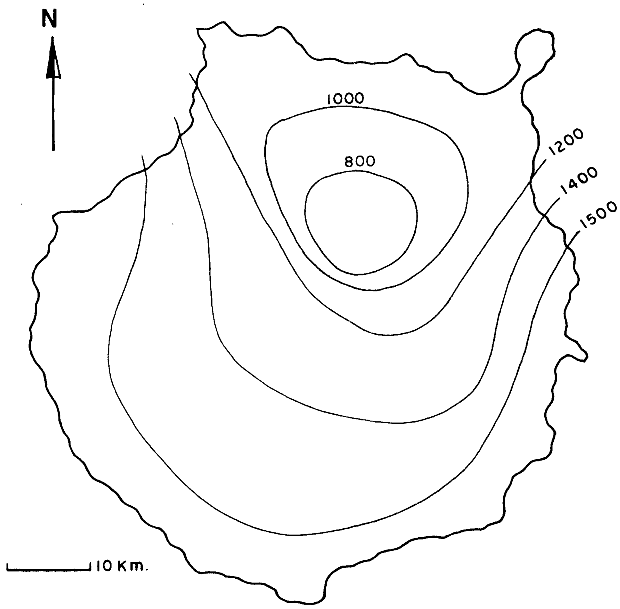

Fig. 7.
Generalized map of average annual potential evapotranspiration in mm.

A generalized map for the annual potential evapotranspiration based on the average values of the years 1971/72 and 1972/73 is shown in Fig. 7. The results of the water balance indicate that these two years can be considered as normal.

The potential evapotranspiration is higher in the southern part of the island than in the northern part, due to the higher temperatures and the more abundant sunshine. In the eastern lower part of the islands the strong winds will also increase the potential evapotranspiration.

Real evapotranspiration

For each zone the soil moisture retention capacity (moisture available between field capacity and wilting point) was estimated. Since no soil maps or land use maps were available for Gran Canaria, aerial photographs, scale 1: 16 000 were used to define vegetation type, soil depth and soil type. The retention capacity was calculated based on estimated values of available moisture for each soil texture, according to Israelsen & Hansen (1962).

In the northern part of the island the average retention capacities varied between 50 and 120 mm and in the southern part between 30 and 60 mm.

In order to permit an evaluation of the real evapotranspiration based on the potential evapotranspiration once the water holding capaciy of the soil is known, several methods are available. For this study the method derived by Thornthwaite & Mather (1957) has been used. This method assumes a linear relationship between the ratio of the rates of real and potential evapotranspiration and the actual soil moisture, which will mean an exponential relationship between real and potential evapotranspiration as is indicated in equation (9).

$$ET = R\,(1\text{-}e^{-\frac{ET_p}{R}}); \qquad (9)$$

where

ET = Real evapotranspiration
ETp = Potential evapotranspiration
R = Soil moisture retention capacity

The real evapotranspiration has been calculated for each of the zones, assuming that the monthly potential evapotranspiration is evenly distributed among the days of the month. For each day with rainfall higher than the potential evapotranspiration, the real evapotranspiration is assumed to have its potential value and the excess of precipitation will either form runoff or infiltrate in the soil. For days with precipitation lower than the potential evapotranspiration and for periods without rainfall, the real evapotranspiration has been calculated from tables based on equation (9).

Recharge from precipitation

In the bookkeeping method of calculation, the actual available soil moisture is calculated for each day or each period between rainfalls as soil moisture at beginning of period, augmented by the excess of rainfall over runoff and diminished by the real evapotranspiration for the period. As soon as the actual available soil moisture exceeded the retention capacity, the excess was considered to form recharge to the ground water body.

Fig. 8 shows a generalized map of the average recharge from precipitation for the two last years and an example of the calculations is given in Fig. 9.

Recharge from stream percolation

Another source of recharge is the stream percolation. This occurs mostly in the lower parts of the rivers where the bottom consists of alluvial deposits.

In the higher parts of the zones used for the water balance, stream percolation is not calculated separately. As all the curve numbers are based on the results

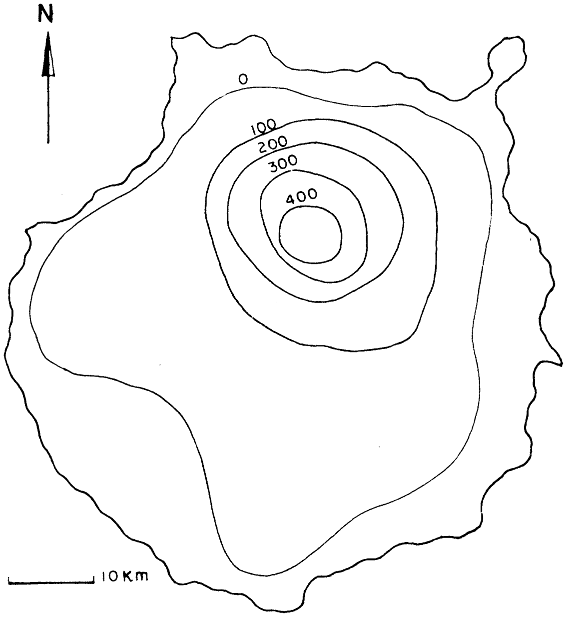

Fig. 8.
Generalized map of the average annual recharge from precipitation in mm.

of the gauged basins, that are all situated in the higher part of the island, the curve number for the higher zones also takes into account stream percolation of the scarce alluvial deposits in the river beds in the higher parts of the basins. Because of the absence of measured flow data in the lower parts of the rivers, stream percolation has been estimated mainly from qualitative data and as such should be considered less accurate and should be subject to revision when measured data are available.

Visual observations as well as verifications in the field if the runoff ever reached the sea for certain storms, have indicated that stream percolation is relatively insignificant in the northern part of the island, but in the southern rivers it is of such a magnitude that it will significantly change the relationship between ground water and surface water. This is also evidenced by the existence of a large number of wells in the southern part of the island which are situated in the alluvial valleys.

Therefore, for each day with runoff in the river according to the calculations, the part of the runoff that would percolate in the riverbeds has been estimated with an ad hoc method taking into account observations made by the Project, ZONA: 5 alta Datos de: Balance Año: 1972 Mes: Febrero CALCULADO POR HZ REVISADO POR LA

Dia	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	Total
P				2	61	3	1	1							2	8						18	45					2	1	144
Qp, CN=63					6																		2							8
ETp	←	6	→	2	2	2	2	2	←	—	—	11	—	→	2	2	←	—	9	—	→	2	2	←	—	7	→	2	2	55
ET	←	5	→	2	2	2	2	2	←	—	—	10	—	→	2	2	←	—	8	—	→	2	2	←	—	7	→	2	2	52
P-ET-Qp					53	1										6						16	41							
H (max=100)	(93)		88	88	100	100	99	98						88	88	94					86	100	100				93	93	92	-1
Rp					41	1																2	41							85

Fig. 9.
Example of calculation.

qualitative information obtained from local inhabitants, the relative magnitude of the alluvial deposits, the existence of wells in the alluvial areas for exploitation of the infiltrated water and the previous moisture conditions. The result has been superimposed on the balance, using equations (3) and (4).

Results of the water balance

For the three hydrologic years 1970/71, 1971/72 and 1972/73, a water balance has been carried out on a daily basis for the 36 areal units defined above, with the total results for the whole island given in Table 3.

Table 3.
Surface water balance for Gran Canaria.

Item	1970/71		1971/72		1972/73	
	mm	Mm^3	mm	Mm^3	mm	Mm^3
P	435	677	300	468	304	474
Qp	74	115	42	66	32	49
Qo	48	75	25	40	12	19
ET	246	384	210	238	199	311
$\triangle$H	+1	+1	0	0	−1	−1
Rp	144	177	48	75	73	114
Rq	26	40	17	26	20	30
R	170	217	65	101	93	144

The first year, 1970/71, was very wet, with a recurrence interval of about once every 10 years. The two subsequent years, 1971/72 and 1972/73, have both been normal since the long-term average of rainfall is calculated at 300 mm. This means that estimates for the median conditions can be based directly on the calculated results for these 2 years.

A check on the accuracy of the results is obtained from an evaluation of the dilution of salts in the ground water which showed a total recharge of 350 Mm^3 for the first 2 years to be compared with the figure 318 Mm^3 calculated in the water balance. Another estimate of the order of magnitude of the average recharge can be based on the average extraction of ground water, which is about 100 Mm^3/year and in Gran Canaria the recharge would be only slightly higher than this figure.

It would therefore seem that this water balance gives results that are compatible with reality for the island as a total, which does not exclude large local discrepancies, especially where basic data are scarce.

DISCUSSION

The presented method for evaluating the surface-water balance is of course not very refined but it is the most detailed method that could be attempted given the time and manpower allotted to the task. Perhaps the most important objective of the water balance was to give an estimate of the recharge to the ground water body, whereas the estimate of runoff could be given a lower priority since most surface water resources are already exploited. Furthermore, runoff is easily seen and reported and in case of having considerable amounts of runoff at a certain location with regularity, almost certainly this would have incited actions for surface water collection. Given the quantity and the quality of present data it is not possible for this water balance to give design data but only to indicate available quantities of water. For designs and for feasibility studies of possible dams, gauging stations should be established and special studies made.

One advantage of the method used is that by working on a daily basis the hydrologist gets a good understanding of what is happening in the basins, whereby many misinterpretations are avoided. This way the fallacy of a constant runoff coefficient was proven. The effect of the rainfall distribution on the other terms of the water balance is illustrated by the following example, which is typical for the northern part of the island. For a total of 200 mm of rainfall in a month and a rainfall-runoff relationship represented by curve number 60, runoff and recharge have been calculated based on the assumptions

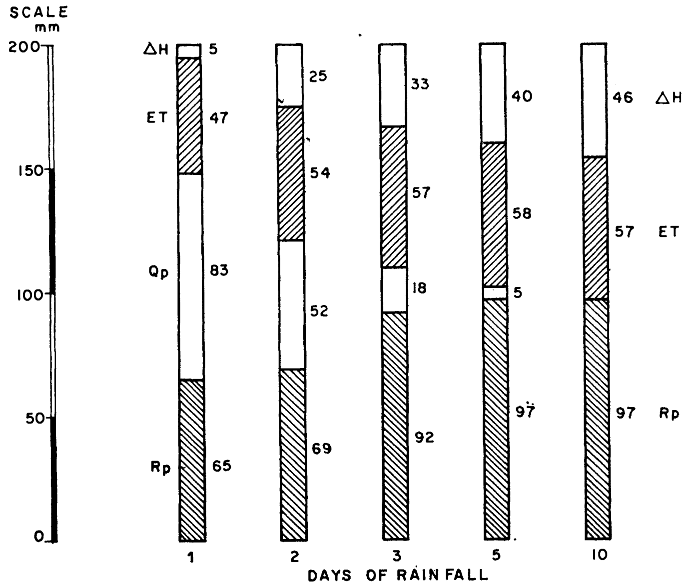

Fig. 10.

Example showing the variation of the terms of the balance for a monthly rain of 200 mm depending on the distribution of the rainfall.

that the soil moisture retention capacity is 100 mm, available moisture is 50 mm at the beginning of the month and the potential evapotranspiration is 60 mm. Five cases were studied with 1, 2, 3, 5 and 10 days of rain per month; rain starting on the first day and the other days equally divided over the month, each day having the same amount of rain. The results are shown in Fig. 10, which is self-explanatory.

Since it seems that this simplified model works reasonably well under the conditions prevailing in Gran Canaria, a logical step would be to improve its accuracy and adapt it for a computer in order to facilitate the calculations. First, however, since no result is of better quality than the input data, these should be improved. More stream gauging and installation of some additional stream-gauging stations, where the infiltration characteristics of the geological formations are not yet known through direct observations, will enable a better estimate of the curve numbers. Land-use maps and soil maps should be prepared and they are imperative not only for work in hydrology. More evaporation pans could be installed.

Once the physical characteristics of the model have been determined with a sufficient degree of reliability the model itself could be refined. Instead of using only a few representative stations for each studied area, computer treatment would permit daily rainfall to be calculated with the Thiessen method. The method could also be refined by taking into account the antecedent moisture conditions which have been disregarded in this first try to prepare a mathematical model for the surface water hydrology of Gran Canaria.

ACKNOWLEDGMENTS

This report has been prepared during the course of an assignment with UNESCO, to which organization the authors are thankful for the permission to publish this paper. The views expressed, however, are those of the authors and are not necessarily shared by UNESCO.

REFERENCES

Israelsen, O. W. & Hansen, V. E. (1962) *Irrigation Principles and Practices.* John Wiley and Sons, Inc., New York.

Soil Conservation Service (1957) *National Engineering Handbook,* Section 4 supplement A, Hydrology. U.S. Soil Conservation Service.

Thornthwaite, C. W. & Mather, J. R. (1957) Instructions and tables for computing potential evapotranspiration and the water balance. Publications in climatology, vol. X, No. 3. Drexel Institute of Technology, New Jersey.

Ven Te Chow (ed.) (1964) *Handbook of Applied Hydrology.* Mc Graw-Hill Inc., New York.

Address:
Södra Stommen 110,
S-43060 Landvetter,
Sweden.

Received 12 March 1974.