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Water balance studies of the Betwa basin

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सार — बेतवा बेसिन, जहाँ अभाव की अवधि के साथ जल आधिक्य वैषम्य की एक ऋतु है, के अध्ययन से यह प्रदर्शित होता है कि ऋतुनिष्ठ कुल वर्षा के साथ अपवाह की तुलना द्वारा वार्षिक मृदा आर्द्रता पुन: आवेश का आकलन किया जा सकता है। निओन सहायक नदी के विस्तृत अन्वेषण से पता चलता है कि कुल वर्षा को मृदा आर्द्रता आपूरण, भौमजल पुन: आवेश और अपवाह के बीच अनुक्रम में वर्गीकृत किया जाता है । एक साधारण प्रत्ययात्मक मॉडल, न केवल अपवाह बल्कि मृदा आर्द्रता तथा उथले भौमजल संग्रहण को भी यथोचित, तैयार कर सकता है।

ABSTRACT. A study of the Betwa basin, where a season of water surplus contrasts with a period of deficit, shows that annual soil moisture recharge may be estimated by comparing seasonal net rainfall with runoff. Detailed investigation of the Nion tributary shows that net rainfall is divided in sequence between soil moisture replenishment, groundwater recharge and runoff. A simple conceptual model reproduces reasonably not only the runoff but also the soil moisture and shallow groundwater storage.

1. Introduction

In the course of the Betwa Project, which was a research programme carried out by the Central Ground Water Board in collaboration with the Natural Environment Research Council, the hydrology of the Betwa basin and its tributaries was studied. Although the overall aim of the project was to develop techniques for assessing the groundwater recharge, the hydrological studies provided an insight into the behaviour of the basin. In particular the inclusion of soil moisture measurements in the water balance study of sample area showed how rainfall was distributed between evaporation, soil moisture, groundwater and runoff during the course of the monsoon. The studies were divided into two main parts; the meteorological and hydrological information available at the start of the study was used to describe the environment in terms of the water balance, and measurements during the course of the study gave more detailed information about the various tributaries and in particular the *Nion*. Because the study included a wet year in 1978 and an exceptionally dry year in 1979, the response of the basin to extremes was sampled.

1.1. *The environment*

The *Betwa*, a tributary of the river *Jamuna*, flowing from Bhopal to Jhansi, drains an area of 20600 km^2 of the Deccan plateau above Dhukwan reservoir. The basin is saucer-shaped, with sandstone hills around the perimeter and an alluvial clay plain in the centre of the basin, where "black cotton soils" overlie weathered basalts at depths varying from 1 to 12 metres (Hodnett & Bell 1986). Shallow groundwater is present in the weathered and jointed basalt in an aquifer which could be extensive but of low permeability. The black cotton soils are dark silty clays up to about 2m thick which have marked swelling and shrinking properties and develop large cracks during the dry season.

The area has generally gentle slopes and a fairly smooth topography, with elevation ranging from 270 to 720 m above sea level. Part of the basin is covered with broad-leaved forest or bush, which is especially thick in the hillier southeast, the wettest part of the catchment. The main species, teak, is deciduous with a brief leafless period from March or April until the monsoon. The forest is fairly widely spread over the basin, apart from the clay plains, but clearance for cultivation has had a considerable effect on its extent; at present about a quarter of the basin contains vegetation ranging from thick forest to scattered bush.

The greater part of the basin, especially the clay plain, is cultivated in the post-monsoon or winter season, with wheat and gram (lentils and chickpeas) as the main crops. Some millet is grown in the monsoon season. Only about 1% of the area was irrigated.

1.2. *Hydrological data*

When the project started in 1976, there were 16 long-term raingauges within the basin (Fig. 3) and others nearby; others were established to give better estimates for certain tributaries. Meteorological observations enabled Penman estimates of evaporation to be made. Inflows to the reservoirs at Dhukwan or at Matatila just upstream had been recorded for 50 years, and gauging stations were installed to measure tributary flows.

2. The surface water balance of the whole basin

The records of rainfall and runoff available at the start of the project were used to study the long-term

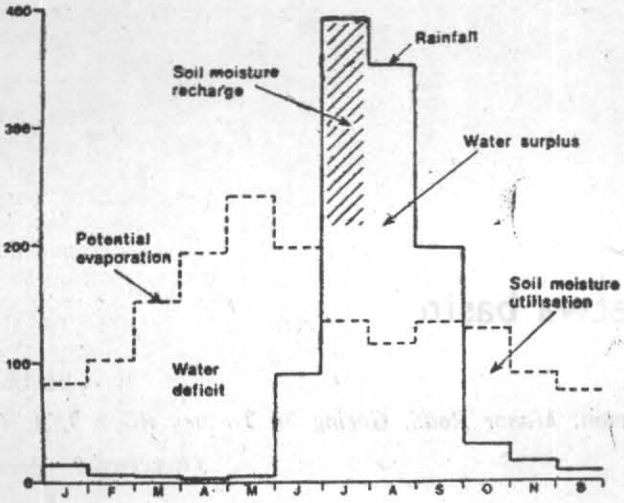

Fig. 1. Annual water cycle in Betwa basin

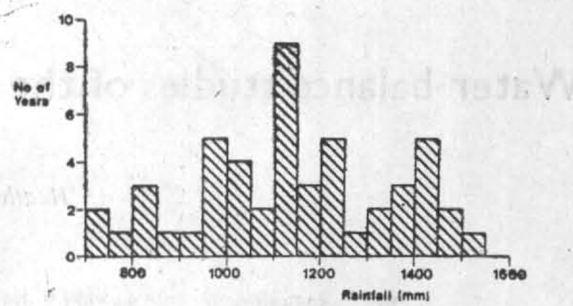

Fig. 2. Betwa basin rainfall histogram, 1926-1975

TABLE 1

Rainfall statistics for standard period, 1926-75

	Period of record	Lat. (°N)	Long. (°E)	Elev. (m)	Monthly mean rainfall (mm) J	F	M	A	M	J	J	A	S	O	N	D	Annual Average (mm*)	Adjusted annual average (mm)	Coeff. of variation
Jhansi	1926-1975	25° 27′	78° 35′	320	14	9	8	3	6	83	302	298	173	32	9	7	944		
Pichor	1926-1975	25 11	78 11	380	13	7	8	1	4	78	309	300	174	30	14	7	945		.340
Dhukwan	1933-1966	25 12	78 2	275	12	5	6	1	3	99	276	285	152	21	6	5	871	866	.409
Chanderi	1962-1975	24 43	78 8	438	2	5	2	0	4	61	366	395	142	7	6	7	996	1048	.470
Lalitpur	1926-1969	24 42	78 25	359	21	10	8	4	4	93	379	332	189	33	16	9	1098	1117	.296
Pachhar	1929-1975	24 34	77 43	502	11	6	5	1	4	92	309	296	160	26	15	8	932		.289
Mungaoli	1926-1975	24 24	78 6	411	16	7	5	1	2	102	318	309	153	31	16	8	968		.292
Sironj	1926-1975	24 6	77 42	465	14	4	6	0	10	103	408	359	187	37	13	4	1037	1038	.324
Korwai	1926-1975	24 8	78 3	400	17	8	7	2	5	113	378	325	173	28	16	7	1079		.300
Khurai	1926-1975	24 3	78 19	431	22	11	7	3	4	116	424	398	204	27	15	9	1240		.283
Basoda	1926-1975	23 52	77 56	415	19	7	6	2	4	130	431	344	204	32	15	8	1205		.320
Berasia	1926-1975	23 38	77 26	478	14	5	5	1	6	110	359	311	193	24	16	7	1060	1059	.309
Vidisha	1926-1975	23 32	77 49	424	17	7	7	3	8	139	462	395	234	38	16	9	1334		.295
Bhopal (Bairagarh)	1930-1975	23 17	77 21	523	15	4	8	3	9	122	420	336	229	33	14	8	1205	1182	.284
Raisen	1926-1975	23 20	77 48	457	14	8	5	3	5	120	433	394	219	32	13	10	1257		.288
Goharganj	1926-1975	23 2	77 40	461	12	8	7	1	5	123	469	404	229	35	15	11	1321		.253
Begumganj	1926-1975	23 36	78 20	550	17	11	9	3	6	125	451	435	242	34	15	9	1358		.276
Ghairatganj	1926-1975	23 25	78 13	521	15	8	7	3	6	122	430	395	222	38	14	9	1270		.277

*Some inconsistencies due to rounding of monthly mns will occur; also, annual averages are computed from years of complete data only, whereas monthlmeans include data from incomplete years.

Fig. 3. Annual average rainfall (mm), 1926-1975

water balance of the whole basin in order to provide a framework for detailed studies.

2.1. *Rainfall*

The climate of the area is dominated by the monsoon from the middle of June to the end of September or beginning of October. An isohyetal map was prepared for the period 1926-75, after monthly and annual averages were computed for stations covering the whole period, and corresponding averages for other stations by comparison. There is considerable variation over the project area in average rainfall, which decreases from over 1300 mm in the southeast, which is hilly and forested, to under 900 mm in the north. The mean annual rainfall for the whole basin is 1138 mm.

The monthly means for the long-term stations (Table 1) show that the seasonal distribution is similar over the whole basin; on average 92 to 95% of the annual rainfall falls between June and September. The variability of annual rainfall at each station is indicated by the coefficient of variability, which changes little over the basin for the long-term stations.

The uniform seasonal and annual variations made it possible to estimate simply the variation from the mean basin rainfall in an individual month or year. After the rainfall at each station was expressed as a percentage of its own long-term station mean, the mean of these station percentages is taken as the index and multiplied by the basin mean annual rainfall to give the basin rainfall for the month or year.

The 1926-75 basin rainfall series was deduced by this method to give a long-term series of rainfall over an area (Sutcliffe *et al.* 1981). The series is summarized in Table 2 and Fig. 1, which demonstrate the marked seasonal distribution, with 65% of the average rainfall in July and August alone and 92% between June and September. The CV of the basin rainfall is reduced to 18.5% compared with 25.3-34.1% at the long-term stations.

The basin annual rainfalls for 1926-75 are presented in histogram form in Fig. 2, which illustrates the symmetrical distribution and the range of values experienced. In order to put the rainfall during the detailed investigation described later into perspective, monthly basin rainfalls, similarly calculated, are given in Table 3. While 1977 and 1978 were slightly above average, the rainfall in 1979 was well below the lowest in 1926-75 in spite of exceptional rainfall in November.

2.2. *Evaporation*

Standard meteorological records were used to estimate open water evaporation and potential transpiration by the Penman equation. The monthly mean values (Table 4) for Bhopal were estimated using local temperature, relative humidity and wind speed measurements, and Nagpur radiation data; Bhopal sunshine records were used to estimate back radiation.

2.3. *Runoff*

Annual total inflows to Dhukwan and Matatila reservoirs were available for the period 1926-75 and were converted to mm over the basin; the mean and variability are summarised in Table 2.

2.4. *The rainfall excess during the monsoon season*

The annual water balance of the Betwa basin may be approached by considering the seasonal cycle as a single period of water excess during the monsoon and a single period of deficit during the remainder of the year.

The problem becomes one of determining whether the seasonal surplus runs off directly or recharges the various sub-surface reservoirs. It is useful to distinguish between replenishment of the soil moisture reservoir which remains for evaporation during the dry season, and recharge of the groundwater reservoir which drains beyond the reach of roots and contributes either to deep storage or to river base flow. In this area the water table approaches the surface in most monsoons, so the soil moisture and the shallow groundwater reservoirs are interlinked, but the soil moisture is retained within the rooting zone for crop water use.

During the monsoon period, monthly rainfall is greater than potential transpiration for between two and four consecutive months, while during the rest of the year potential transpiration exceeds rainfall except in the occasional month. Fig. 1 shows for the average year the period of surplus or excess of rainfall over evaporation, and the subsequent period of deficit. The period of

TABLE 2

Mean rainfall and runoff for Betwa basin and variability (mm), 1926-75

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual rainfall	Annual runoff
Mean	15	7	6	2	5	111	390	351	196	31	15	8	1138	351
SD	17	12	11	3	9	76	128	118	119	36	34	19	211	157
CV(%)	111	165	179	161	183	68	33	34	61	118	230	230	18.5	44.7

TABLE 3

Average rainfall over Betwa basin, 1976-79

	J	F	M	A	M	J	J	A	S	O	N	D	Total
1976	10	4	4	1	12	106	231	303	204	2	15	1	893
1977	1	7	5	4	5	210	299	403	196	15	30	3	1178
1978	4	26	3	3	0	195	356	443	96	0	0	37	1163
1979	27	30	2	0	14	71	162	142	29	1	128	7	613
Mean (1926-75)	15	7	6	2	5	111	390	351	196	31	15	8	1138

TABLE 4

Open water evaporation (E_0) and potential transpiration (E_T) estimated by the Penman method (Plinston and Hill 1970)

(Bhopal : 23°17′N, 77° 21′E, 523 m)

	J	F	M	A	M	J	J	A	S	O	N	D	Annual
E_0	113	135	193	241	293	237	164	143	167	165	123	103	2077
E_T	83	102	152	193	241	197	134	115	133	127	90	75	1643

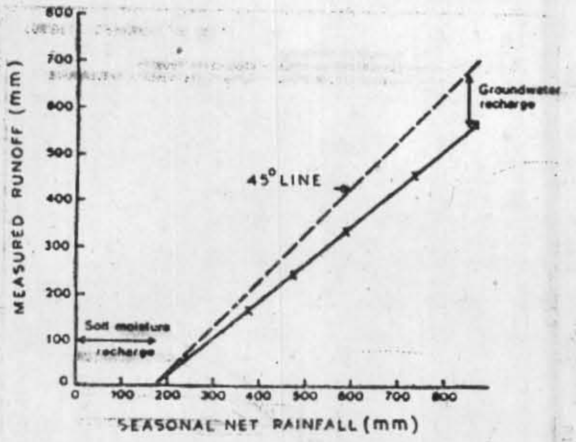

Fig. 4. Schematic comparison of runoff with seasonal net rainfall

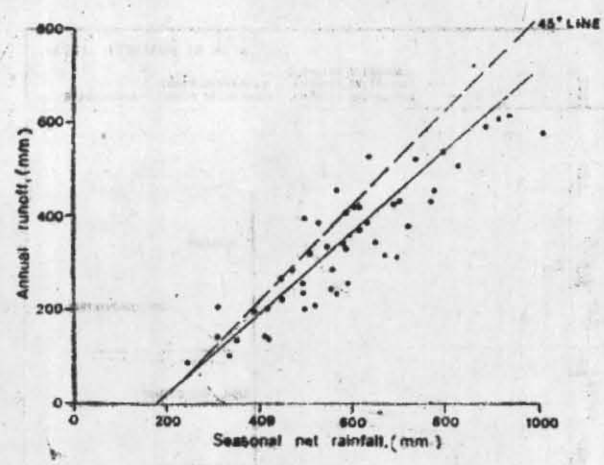

Fig. 5. Seasonal net rainfall and annual runoff, Betwa basin, 1926-1975

soil moisture replenishment, followed by a period of water surplus, may be included on this diagram, and then after the end of the monsoon a period of soil moisture use followed by a period of water deficit. In the Betwa basin, where the soil moisture storage reaches wilting point during the dry season and fills during the monsoon, the annual replenishment will bring the storage from wilting point to field capacity throughout the profile. This replenishment should be reasonably constant from year to year, in the absence of land use change, and may be considered as a first charge on the net rainfall, or excess of rainfall over evaporation.

The seasonal net rainfall during each monsoon can be estimated by subtracting monthly potential transpiration from the monthly catchment rainfalls and adding the positive values of these net monthly figures to give the seasonal surplus (Because monsoons do not begin and end with calendar months, the use of 10-day figures might be preferable, but these are not generally available).

Once the soil moisture has been replenished, the surplus is divided between groundwater recharge and surface runoff. Recharge raises the water table in the shallow aquifer, usually to the surface in this area, and storage therefore goes above field capacity to saturation; the excess may be regarded as groundwater storage, much of which provides about 30 mm or so of river baseflow after the monsoon. When the profile is saturated, there must be some percolation below the surface aquifer as well as surface runoff.

If one accepts that annual soil moisture recharge is a fixed charge on the net rainfall, and also assumes that the surplus is divided proportionately between runoff and groundwater recharge, it is possible to make deductions about both processes by comparing seasonal net rainfall with annual runoff as in Fig. 4. The soil moisture replenishment is the intercept on the horizontal axis, r the net rainfall required before any runoff occurs; e groundwater recharge is the divergence between e 45° line and the net rainfall/runoff points. However, the accuracy of this recharge estimate depends on all the estimate including evaporation.

2.5. *Comparison of seasonal rainfall excess with runoff*

This approach is most directly applicable to a basin whose land use is reasonably homogeneous, because the rooting depth and thus the soil moisture recharge and actual evaporation will be uniform. On the other hand, a portion of the Betwa basin is covered with forest on the sandstone hills, and about 10% of the plains is covered by grass and scrub which extracts water to about 4-5 m and continues to transpire into the dry season. When studying the water balance of the whole basin, it is necessary to treat the basin as homogeneous.

The rainfall and runoff records for 1926-75 were compared in this way. Fig. 5 shows the seasonal net rainfall, neglecting the occasional heavy rainfall in November or December, compared with the runoff expressed in mm over the whole basin. In view of the scatter, a line has been fitted by eye ignoring the 1930 and 1971 outliers. This shows that soil moisture replenishment is about 175 mm. The 45° line is drawn and suggests that the annual groundwater recharge is about 50 mm, but this should be compared with the scatter of the points; this comparison illustrates the difficulty of estimating groundwater recharge from the differences between other quantities.

The groundwater recharge which returns to the river and emerges as base flow during the dry season can be deduced by study of the monthly flows in such a climate. Flow records for the whole basin suggest that this base flow component is of the order of 30-50 mm.

2.6. *Summary of long-term water balance*

The 50-year series of monthly rainfall for the Betwa basin can be expressed as gross rainfall or net rainfall after subtracting estimated evaporation and compared

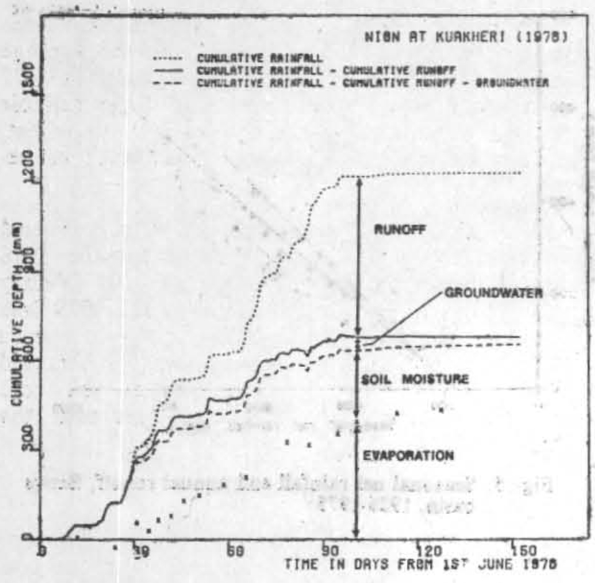

Fig. 6. Cumulative water balance, Nion basin, 1978

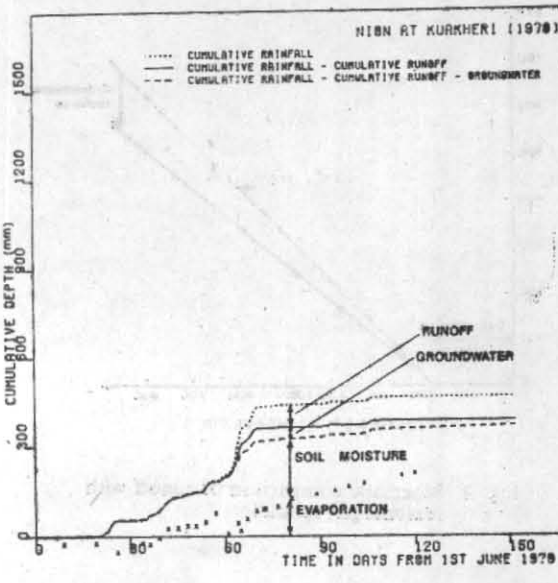

Fig. 7. Cumulative water balance, Nion basin, 1979

TABLE 5

Summary of water balance for Nion basin, 1978 and 1979

Date	Rainfall (R)	Runoff (Q)	Potential transpiration (E_T)	Soil moisture (S)	δS	Well depth (m) G	δG (c=0.01)	$R-Q-\delta S-\delta G$
				1978				
1-25 Jun	126.28	3.73	164.39	0	148.26	5.97	—1.50	—24.21
26 Jun-10 Jul	331.61	89.74	52.42	148.26	102.46	6.12	37.60	101.81
11 Jul-6 Sep	765.62	445.66	197.56	250.72	—14.57	2.36	12.20	322.33
7 Sep-31 Oct	11.19	16.30	256.41	236.15	—23.96	1.14	—25.20	44.05
Total	1234.70	555.43	670.78	212.19	212.19	3.66	23.10	443.98
				1979				
1 Jun-31 Jul	202.83	6.18	348.88	23.93	169.35	5.98	—2.48	29.78
1-12 Aug	229.41	66.82	44.00	193.28	29.72	6.23	43.99	88.88
13 Aug-30 Sep	31.23	6.59	245.02	223.00	—75.01	1.83	—15.97	115.62
Total	463.47	79.59	637.90	147.99	124.06	3.42	25.54	234.28

All variables are in mm, except for well depth in m. is change in soil moisture, δG is change in well depth × coefficient of storage, *i.e.*, chge in aquifer storage.

with annual runoff records for the same 1926-75 period to give the following summary of the water balance :

		Standard deviation	Coefficient of variability
Gross rainfall	1138 mm	211 mm	18.5 %
Net rainfall	583	170	29.2
Runoff	351	157	44.7

The standard deviation of annual runoff is very similar to that of net rainfall, but when expressed as a percentage of the mean its position as a residual makes it much more variable. Comparison of the annual values of the seasonal surplus and runoff show that the seasonal soil moisture replenishment can be estimated as about 175 mm over the basin, though physical studies have shown that there are differences between various land use types. This figure has a number of practical implications, as it is the amount of storage available for flood attenuation and is also available for crop growth after the monsoon each year. Although an estimate of groundwater recharge of about 50 mm was deduced from the water balance, this estimate is smaller than the scatter of the data, and physical studies are required to measure more precisely the groundwater recharge which takes place locally to maintain baseflow or to deeper water bodies.

3. The surface water balance of the Nion tributary—Hydrological measurements

The hydrology of the area can be studied by more detailed physical measurements in a typical tributary basin. Rainfall and runoff records can be supplemented by observations of soil moisture storage and groundwater conditions. These additional measurements were made during 1978 and 1979 for the Nion basin (Sutcliffe and Green 1986), and show that the basin reacts to the monsoon in a sequence of four phases; soil moisture replenishment, groundwater recharge and runoff combined, runoff alone and finally recession.

The records comprise six rainfall stations, a river flow station, a meteorological station at Bhopal from which evaporation may be estimated, a set of soil moisture sites and five well level recorders. The six rainfall records were combined to give daily basin rainfall, which was generally representative though on occasions storm incidence was very variable. The gauging station was rated by current meter and floats; level changes can be large and rapid, but hourly levels were used to define daily flows. Monthly evaporation estimates may be derived by the Penman method, but as daily estimates were required these were calculated from maximum and minimum temperatures and solar radiation at the top of the atmosphere using an empirical relationship based on the Penman approach (Murthy *et al.* 1972).

Soil moisture storage was measured regularly by neutron probe at a network of access tubes across the Nion basin. From September 1977 to September 1978 eight tubes were measured sampling the land use of the basin, with five in wheat, two in dal (lentils) and one in grass and shrubs. The transpiration during the dry season and recharge during the monsoon was much greater (450 mm) at this last site with its deep roots than at the other sites (200 mm), but reasonable values for the basin storage were obtained from the average storage to 2.1 m depth at all eight sites. In 1978-79 the full network was discontinued, but a less reliable estimate was obtained from four sites (one in wheat, two in dal, one in grass) weighted 5, 2 and 1 as before.

The mean depth at five observation wells was used to estimate daily ground water storage for the 1978 monsoon, using a storage coefficient of 0.01 (Versey & Singh 1982). A corresponding series for 1979 was obtained from the single well operating. When wells rise above 2.1 m depth the storage was subtracted from the measured soil moisture storage to avoid double counting since the water-table rises near the surface in most monsoons.

3.1. *Water balance sequence*

The hydrological data for the 1978 and 1979 monsoons are summarised in Figs. 6 and 7, with the soil moisture and groundwater storages expressed as mm above 1 June. The sequence of events is revealed more clearly by presenting the water balance in cumulative form, with rainfall distributed between runoff, groundwater and soil moisture storage, and evaporation. The scatter in the points marking the boundary between soil moisture and evaporation illustrates the difficulty of obtaining representative measurements, but it is apparent that actual evaporation starts after an initial amount of rainfall and continues at a steady rate until the end of the monsoon when it decreases sharply.

The diagrams show the timing of the four phases of the basin response in the different years. In the first period the rainfall goes to soil moisture replenishment; in the second period this continues but the shallow aquifers respond to groundwater recharge and some runoff occurs ; in the third phase there is little further change in soil moisture or groundwater storage and the bulk of the net rainfall becomes runoff, which is concentrated in this period; in the fourth period the base flow runoff is maintained from groundwater recession, and evaporation is maintained from soil moisture storage.

The water balance during each of these periods in 1978 is summarised in Table 5. This shows that soil moisture recharge reaches 150 mm before significant groundwater recharge or runoff occurs, and that evaporation is negligible at this stage. A further 100 mm of soil moisture recharge in the next period coincides with ground water recharge (40 mm) and some runoff (90 mm), while most of the runoff (450 mm) occurs later. In the last period runoff is approximately equal to the fall in groundwater storage, and actual evaporation, maintained from soil moisture storage, is low as the area is fallow and harrowed to conserve water. The water balance during the subsequent crop season has been described by Hodnett and Bell (1986). The crops draw steadily on soil moisture storage, supplemented by the winter rains, during the growing season from the end of October to harvesting in March.

The water balance for 1979 is illustrated in Fig. 7 and summarised in Table 5. It is very different from 1978 because of the very low monsoon rainfall, but the

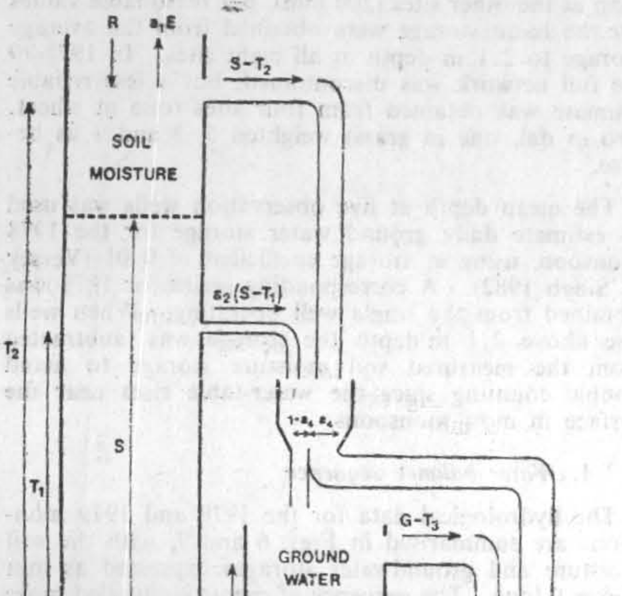

Fig. 8. A conceptual model of the Nion basin

sequence of events is similar. It is the later processes, like groundwater recharge and especially runoff, which are most severely affected by the low rainfall; soil moisture replenishment is little lower than in 1978, while evaporation is reduced. The dates for the various phases of recharge differ in the two years, but the processes and even the depth of rainfall which is required before runoff occurs, are very similar in the two contrasting years.

3.2. *A conceptual model of the Nion basin*

This description of the behaviour of the basin needs to be expressed in the form of a model if it is to be useful in other basins or in other years. Conceptual models have been applied to Indian hydrological data (Abbi *et al.* 1980). A simple conceptual model, based on observation of the way in which the various processes are linked, is illustrated in Fig. 8.

The rainfall R is added to the soil moisture store S; when this store exceeds a first threshold T_1, evaporation occurs at a rate a_1E proportional to potential transpiration, and drainage $a_2(S—T)$ to groundwater and runoff is proportional to this storage; when the soil moisture store S exceeds a higher threshold T_2, then all the excess is diverted to groundwater and runoff. The proportion of this drainage which goes directly to runoff is fixed by a parameter a_4 (between 0 and 1). When water is available in the groundwater store G there is drainage to runoff (a_3G) which is proportional to this store ; when G exceeds a threshold T_3 the excess runs off directly. There is also a small allowance of 0.075 mm/day to allow for losses before the monsoon. The runoff is routed through a linear reservoir so that $Q=a_5V$. At the end of the monsoon, during the fallow season, the evaporation falls to 0.25 a_1E ; this period was defined as having less than 20 mm rain in the preceding 10 days.

Although this model has eight parameters (a_{1-5} and T_{1-3}), it is simple to understand and the parameters can be thought of as having physical meanings. For instance T_1 is the soil moisture storage at which significant drainage begins and T_2 corresponds to the total soil moisture capacity; similarly T_3 is the storage available for groundwater. The parameters a_2 and a_3 are recession constants in the exponential drainage from soil moisture and groundwater stores, while a_1 is a ratio of actual to potential transpiration, and a_4 is a direct runoff coefficient.

Because direct measurements of soil moisture and groundwater are available, some of these parameters can be estimated directly and others can be adjusted by comparing predictions within the model with measurements. Normally the only output of a model is a runoff series and there is so much interference between the model parameters that it is difficult to optimise the individual parameters (Nash and Sutcliffe 1970). This mixture of physical reasoning and subjective fitting gave the following values for daily operation of the model :

$a_1=1.0$	$a_5=1.8$
$a_2=0.0025$	$T_1=150$ mm
$a_3=0.114$	$T_2=250$ mm
$a_4=0.65$	$T_3=50$ mm

Comparison between predicted and observed values of soil moisture storage, groundwater storage and runoff in 1978 and 1979 are shown in Figs. 9 and 10. Bearing in mind that the soil moisture observations are not continuous, and may not be representative in 1979, the fit in three independent sets of observations suggests that a reasonable representation of the physical processes has been achieved. The success of the model supports the belief that the behaviour of the area can be described very simply even in such contrasting years at 1978 and 1979. The main contributions to groundwater storage and runoff occur when the soil moisture store is full, and the periods when the soil moisture and shallow groundwater systems are full can be predicted with a simple model. It is during these periods when deep recharge might occur, but evidence of recharge must be sought from direct measurements rather than water balance alone.

4. The water balance of other tributaries

Additional information on the water balance of the area is provided by records of rainfall and runoff from other tributaries. The runoff coefficient varied markedly between wet and dry years, as shown on the Nion basin, but also varied according to topography between the flatter drier tributaries and the steeper wetter ones. However, comparisons of cumulative rainfall and runoff, similar to those made for the Nion, suggest that the same sequence of events—soil moisture recharge followed by groundwater recharge and runoff—occurs in the other tributaries. The initial rainfall required to fill the soil moisture storage sufficiently for runoff to occur varies over the basin from 100-150 mm for the *Bina*

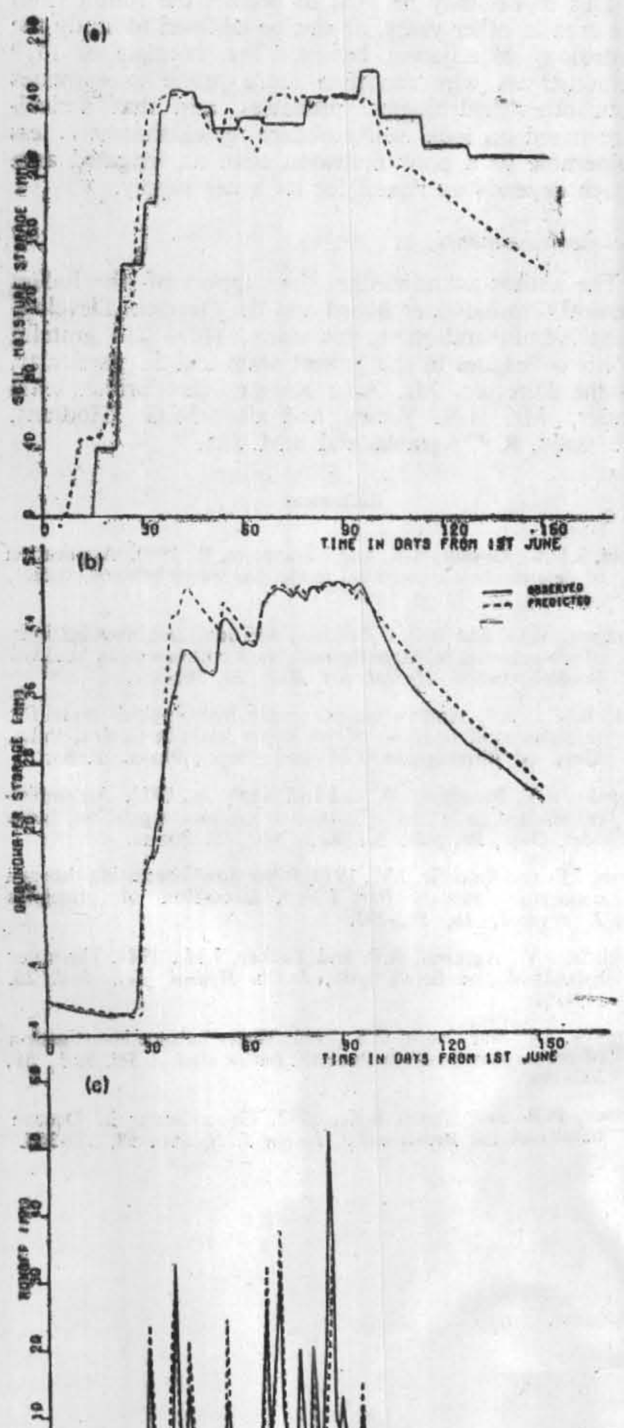

Fig. 9. Observed and predicted soil moisture storage, groundwater storage and runoff : Nion basin, 1978

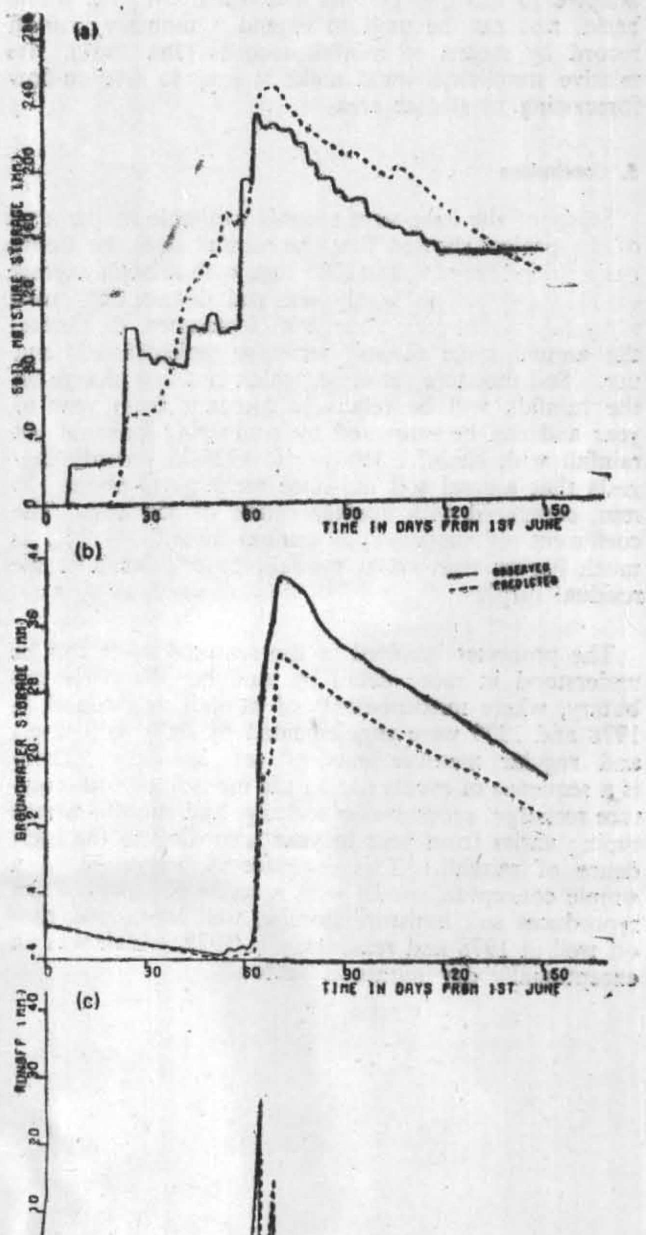

Fig. 10. Observed and predicted soil moisture storage, groundwater storage and runoff : Nion basin, 1979

tributary in the southeast which is relatively steep with shallow soils, to 250-300 mm for western tributaries where the proportion of shrub and perennial grass is higher and the soils are shallow and groundwater recharge easier.

More evidence on the groundwater regime may be obtained from a study of baseflow, the steady component of river flow. It is possible to separate baseflow from direct runoff during the monsoon by subjective analysis of recession curves, but it is particularly useful to study baseflow runoff after the end of the monsoon as it provides a simple estimate of groundwater storage. For most stations, this varied from 22 to 50 mm in the wet years 1977-78.

The model developed for the *Nion* tributary was adapted to monthly periods and tested over the whole basin, and can be used to extend a monthly runoff record by means of rainfall records (Jha 1981). Its relative simplicity would make it easy to test in-flow forecasting in similar areas.

5. Conclusions

Study of the long-term records available at the start of the project showed that the rainfall over the Betwa basin varied from 900 to 1300 mm, with a basin average of 1138 mm. The highly seasonal distribution, with 92% falling between June and September, dominates the annual cycle of soil moisture replenishment and use. Soil moisture recharge, which is a first charge on the rainfall, will be relatively constant from year to year and can be estimated by comparing seasonal net rainfall with runoff. Study of 1926-75 records suggests that annual soil moisture recharge is about 175 mm, compared with average runoff of 350 mm. The coefficient of variation of annual runoff, 44.7%, is much higher than basin rainfall, 18.5%, as it is the residual surplus.

The processes involved in the seasonal cycle can be understood in more detail by studying the *Nion* tributary, where measurements of rainfall and runoff in 1978 and 1979 were supplemented by daily well levels and regular measurements of soil moisture. There is a sequence of events during the monsoon—soil moisture recharge groundwater recharge and runoff—whose timing varies from year to year according to the incidence of rainfall. This sequence is expressed in a simple conceptual model with a series of stores which reproduces soil moisture storage, well levels and runoff well in 1978 and reasonably in 1979, which was an exceptionally dry monsoon season.

This model may be used to predict the runoff from the area in other years, or can be adapted to study the hydrology of adjacent basins. The example of 1979 demonstrates why runoff is more prone to extremes than other hydrological processes, and that agriculture based on local soil moisture replenishment is less vulnerable to a poor monsoon than an irrigated area which depends on runoff for its water supply.

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