Rainfall-Runoff Data and Modelling in the Likhu Khola Catchment, Nepal

David Boorman, Alan Jenkins and Robert Collins
Institute of Hydrology, Wallingford,
Oxfordshire, OX10 8BB, UK

Abstract

Hydrological and meteorological data have been collected from seven sites in the Likhu *Khola* in Nepal's Middle Hills. The rainfall data have been examined on three time scales: seasonally, monthly, and hourly. For longer durations, the data show the typical pattern of a monsoon climate with over 90 per cent of the annual fall occurring in the wet season. Possible systematic variations in long-term rainfall with altitude and aspect were noted. The hourly data from the gauges show that rainfall is usually contemporaneous at all gauges, but that the amount of rainfall can vary greatly between sites within any rainfall event. The gauges show the same diurnal patterns, with rainfall most likely to occur in the early hours of the morning and least likely to occur in the late morning. Flow data from three catchments with differing land use have been derived. Together with the rainfall data, they have been used to develop and calibrate a simple, lumped rainfall-runoff model using daily data. The model gives additional insights into the processes occurring within the catchment and aids qualitative assessment of the data. Variation in model parameters may be linked to physical attributes of the catchments.

Introduction

Population growth in the Himalayan region has led to an increased demand for food, which has been met by the increased use of fertilizers and the expansion of agricultural land. These changes modify the quality and quantity of river flows downstream from the affected areas and therefore have a regional as well as a local impact. To investigate such changes requires good-quality hydrological data on the appropriate spatial scale and temporal resolution. To enable such a study, flow and rainfall, volumes and quality, together with other meteorological data, were collected from five sub-catchments of the Likhu *Khola* as part of a larger study entitled *Land Use, Soil Conservation and Water Resource Management in the Nepal Middle Hills* by Gardner and Jenkins (1995). This paper describes the rainfall and runoff data collected from these sites, analyses of the data, and results from a rainfall-runoff model used to simulate catchment response.

Meteorological Data

Data were collected at seven sites, listed in Table 1, between 1991 and 1994. Five of these are flow sites at which stream-water level (stage) and rainfall, along with other hydrometeorological parameters, were recorded at 30-minute intervals. These sites were selected so that the catchment areas represented the different land uses (forest, cultivated land, and grass) and contrasting aspects within the Likhu *Khola* basin, which has steep north- and south-facing valley sides. A simple land-use classification of the catchment area is shown in Table 1. At the two other sites, an automatic weather station (AWS) was installed to record rainfall and other meteorological data on an hourly basis. Because not all gauges were installed at the start of the project, and there were a number of technical and operational problems leading to loss of data, the data sets are by no means complete.

Table 1 Characteristics of the Study Sites

Name	Type	Altitude	Aspect	Catchment Characteristics (flow sites only)			
					Land Use		
		(m)	(facing)	Area (km^2)	Forest	Cultivated	Grass
Baseri	AWS	700	S				
Bhandare	Flow	700	N	1.43	9%	90%	1%
Bore	Flow	700	N	4.23	60%	39%	1%
Chinniya	Flow	1300	N	1.14	83%	17%	0%
Dee	Flow	800	S	2.64	15%	59%	26%
Gerogoan	AWS	800	N				
Jogi	Flow	700	N	2.35	2%	96%	2%

The general climatic pattern revealed by the data from these gauges corresponds to other data from the region. The annual rainfall at the AWS sites for the year starting in October 1992 was just over 2,000mm, of which over 90 per cent fell in the wet season between 1 April and 30 November. Note that this *wet season* corresponds to both the monsoon and pre-monsoon periods, and this term will be used throughout this paper to refer to this period. At the nearby, but higher, Kakani long-term meteorological station, the long-term average rainfall is greater, 2,804mm for the period from 1962 to 1991, with an almost identical seasonal pattern.

Of the study sites, the Chinniya, which is the highest site and on a north-facing hillside, has the greatest rainfall, on average roughly 25 per cent more than the sites in the valley bottom. The Gerogoan site, also on a north-facing slope, receives an average of about 10 per cent more than the other lower sites. The tentative conclusions are, therefore, that rainfall increases with altitude and is greatest on the north-facing side of the valley. The latter is expected as most storms arrive at the catchment from the south or south-east. However, other sites in Nepal report a more complex relationship of rainfall with altitude, e.g., the study by Higouche et al. (1982) along the Imja *Khola*.

A monthly-based analysis of the data again shows the same general rainfall patterns at all sites, with peak rainfalls occurring in July and August, and insignificant rainfall outside the wet season. However, there is considerable variability both within wet seasons between gauges and from year to year at each gauge, but this is typical of rainfall data recorded at a great many sites around the world and serves as a reminder of the danger of trying to draw climatological inferences from such short records.

Whereas the monthly and seasonal rainfall patterns observed at these sites can be seen as supporting the already known climatic patterns of the region, analysis of the rainfall data on an hourly basis reveals fresh insights into the local climate of the Likhu *Khola*. The rainfall that occurred during one five-day period at five of the rain gauges, shown in Figure 1, illustrates many of the features typical of rainfall during the wet season. Throughout the five days, rainfall occurred at the same time at all gauges. However, whereas for some storms the rainfall profiles and depths are similar, e.g., the event starting early on 3rd August, for the others this is not so. This pattern indicates that the rainfall distributions are generally produced by large-scale effects but that local influences cause significant differences.

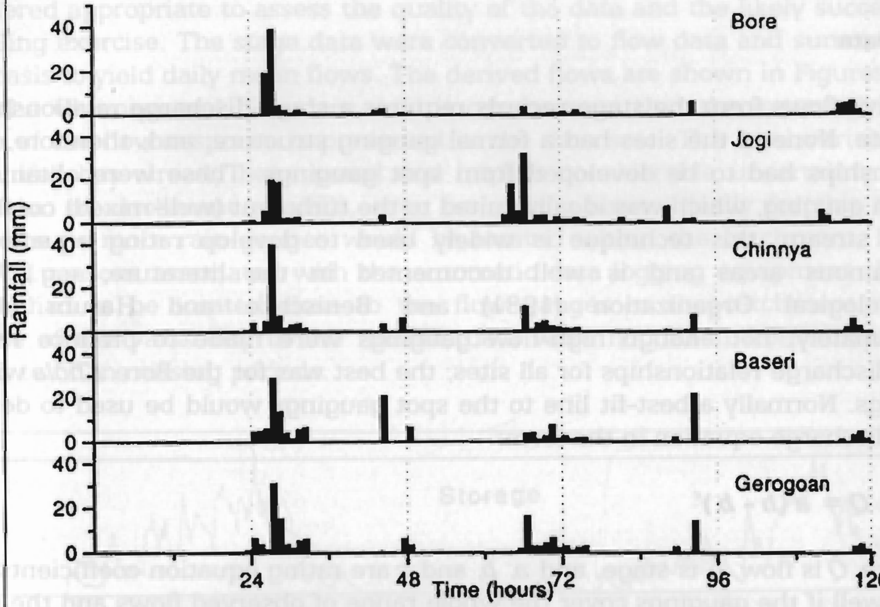

Figure 1: Hourly Rainfalls at Five Gauges for the Five-day Period Starting 2nd August 1993

An analysis of rainfall bursts and depths shows that the rainfall regime is very similar at the gauges, with the only difference being in longer-term average rainfalls, as already noted. The following conclusions can be drawn from the analysis.

i. The diurnal variation of rainfall shows that rainfall is least likely between 08.00 and 12.00, and most likely between midnight and 04.00.
ii. Average storm durations are between six and eight hours, but frequently contain short periods with no rainfall.
iii. Intervals between storms are usually either less than two days or greater than four days.
iv. Storms usually cause rainfall at all sites, although rainfall totals can vary greatly between sites.

v. Most of the rainfall is in low-intensity bursts, e.g., at the Jogi 80 per cent of the rainfall was in bursts containing less than 10mm of rainfall and only five per cent in bursts containing 40mm or more.
vi. Within storms there were very high-intensity bursts of short duration, the maximum being a rate of over 2mm/minute.

The data from the Baseri and Gerogoan weather stations allow a comparison between the climate of the south- and north-facing valley sides. The most striking difference noted was that the south-facing site, Baseri, had maximum daily temperatures up to 5°C hotter than the north-facing site. This difference would be expected to cause a difference in evaporation and, hence, soil moisture, which would in turn cause different flow regimes in north- and south-facing catchments.

Flow Data

To derive flows from the stage records requires a stage-discharge relationship for each site. None of the sites had a formal gauging structure, and, therefore, these relationships had to be developed from spot gaugings. These were obtained by dilution gauging, which was ideally suited to the turbulent (well-mixed) conditions in the stream; this technique is widely used to develop rating equations in mountainous areas and is well documented in the literature, e.g., World Meteorological Organization (1981) and Benischke and Harum (1990). Unfortunately, not enough high-flow gaugings were made to produce reliable stage-discharge relationships for all sites; the best was for the Bore *Khola* with 27 gaugings. Normally a best-fit line to the spot gaugings would be used to derive a stage-discharge equation in the form:

$$Q = a(h - b)^c$$

in which Q is flow, h is stage, and a, b, and c are rating equation coefficients. This works well if the gaugings cover the whole range of observed flows and the rating equation is primarily interpolating between gaugings. However, the rating equations for these catchments had to be extrapolated considerably beyond the highest gauging, and so rating equations were obtained by fixing the exponent, c, according to the physical nature of the gauging sites and fixing a and b with reference to the spot gaugings.

Two features of the flow data are common to all catchments. Firstly, flows outside the wet season are very low, and even fairly intense rainfall at this time causes little or no increase in flow. Secondly, during the wet season, flows are maintained at higher levels, and there is a very rapid but short-lived response to all rainfall events. Clearly, at the onset of the wet season a large proportion of the rainfall is stored by the catchment, and rain falling later is on a (partially) saturated catchment and runs off quickly.

None of the south-facing catchments yielded sufficient flow data to enable a comparison of the flow regimes with the catchments on the north-facing slopes.

While some general conclusions can be drawn from separate analyses of these data (i.e., flow, rainfall, and potential evaporation), it is far more revealing to examine them together within the framework of a rainfall-runoff model. The disadvantage of such an approach is that it requires all three data types to be available for the same period. For the Chinniya, the period from March 1992 to October 1993, encompassing the majority of two wet seasons, is fairly complete, as is the one year period from March 1992 on the Bhandare and Bore catchments. These data have been used to develop and calibrate a rainfall-runoff model.

Rainfall-Runoff Modelling

The modelling exercise has been carried out using daily data, as this was considered appropriate to assess the quality of the data and the likely success of a modelling exercise. The stage data were converted to flow data and summed on a daily basis to yield daily mean flows. The derived flows are shown in Figures 2 and 3 for the Chinniya and Bhandare, and it can be seen that the extremely flashy nature of the flow response is preserved in the data sets. The local variability of the rainfall has already been noted and implies considerable uncertainty in the estimation of catchment rainfalls, even on a daily basis. Ideally for this type of study one or more rain gauges would be located within the catchment, but for logistical reasons associated with the automatic data logging equipment the rain gauges had to be located close to the flow gauges at the catchment outlets. Because of the variability in the rainfall, data were not taken from distant rain gauges to fill in missing periods.

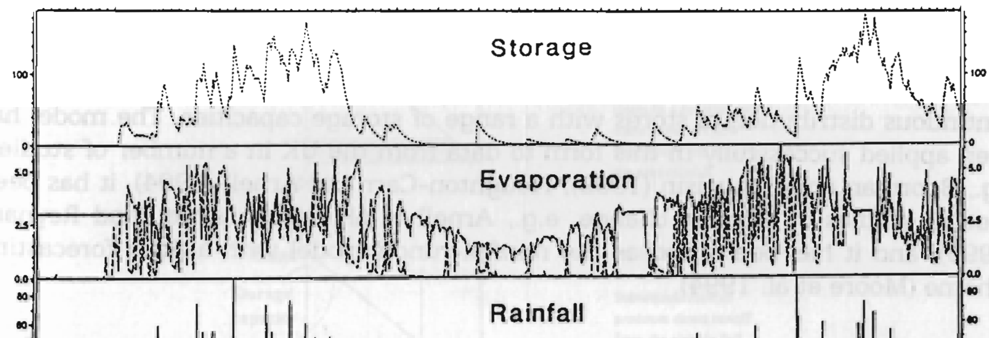

Figure 2: Soil-water Storage, Observed Potential Evaporation (dot-dash line) and Simulated Actual Evaporation (dashed line), Rainfall, and Observed (solid line) and Simulated Flows (dotted line) for the Chinniya *Khola* for the period from March 1992 to October 1993 (Abscissa scale in days, ordinate scales all in mm)

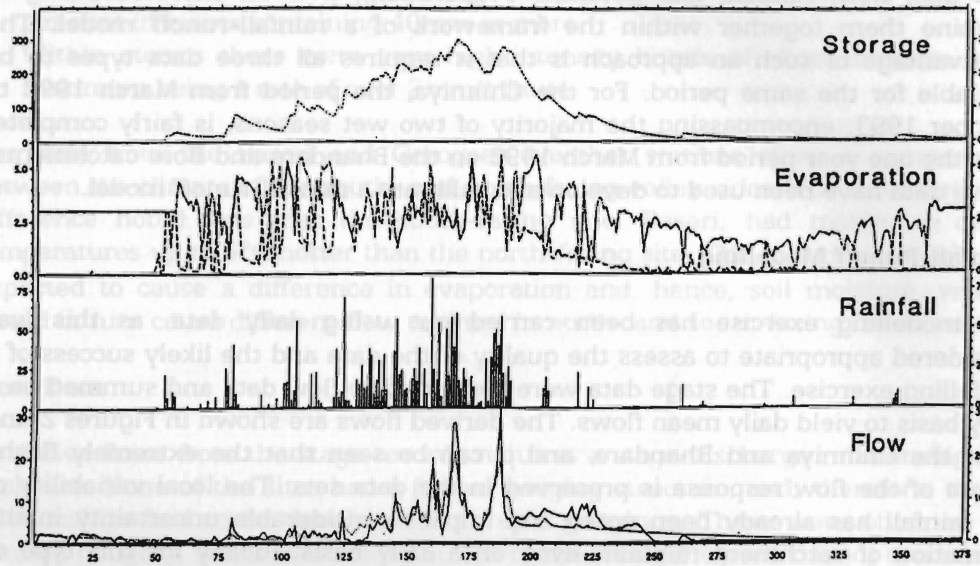

Figure 3: Soil-water Storage, Observed Potential Evaporation (dot-dash line) and Simulated Actual Evaporation (dashed line), Rainfall, and Observed (solid line) and Simulated Flows (dotted line) for the Bhandare *Khola* for the period from March 1992 to March 1993 (Abscissa scale in days, ordinate scales all in mm)

The model chosen was based of the probability distributed storage principle proposed by Moore (1985) in which the soils of a catchment are represented by a continuous distribution of stores with a range of storage capacities. The model has been applied successfully in this form to data from the UK in a number of studies, e.g., Boorman and Bonvoisin (1992); Houghton-Carr and Arnell (1994), it has been used in studies of climatic change, e.g., Arnell et al. (1990); Arnell and Reynard (1993), and it has been used as the rainfall-runoff model with a flood forecasting scheme (Moore et al. 1994).

Within the model, the storage capacity of the distribution of stores ranges from zero to a maximum value, S_{max}. Describing how this array of stores functions is explained by describing their operation, starting from the situation in which all stores are empty and there is no loss through evaporation.

Rain falling on the catchment (P mm) will completely fill all stores with a capacity of less than P mm and add P mm of water to all of the stores with greater than P mm capacity (Fig. 4i). The 'excess' rainfall that fell on the stores with capacity less than P mm flows directly to a channel which is routed via a linear reservoir to the catchment outfall as quick-response runoff. During the time interval, drainage from the soil store occurs at D mm per time step. When the drainage rate, D, is greater than the rainfall rate, then all the stores empty and the soil store returns to its initial state (i.e., totally drained), but when D is less than P, the situation is more complex. Those stores with a capacity >P mm now hold P-D mm, those with a capacity of less than D mm are emptied, and, between these two values, water content increases linearly (Fig. 4ii). The water stored within the soil is then assumed to be redistributed so that the content of each store is the same; a certain percentage of the stores will therefore now be full to capacity, representing saturated conditions in the soil (Fig. 4iii). If there is rainfall in the next interval, then a percentage of this will fall on saturated stores and become excess rainfall, an additional set of stores will become saturated and also contribute to excess rainfall, and the contents of the remaining stores will increase (Fig. 4iv). For as long as the rainfall rate exceeds the drainage rate, the catchment becomes more saturated and the percentage contribution to excess rainfall increases.

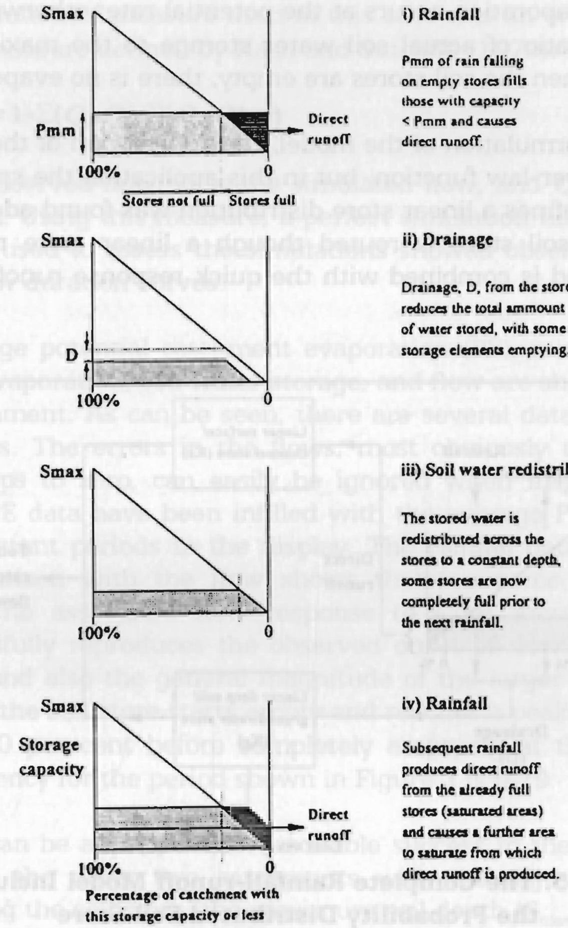

Figure 4: Operation of the Probability Distributed Soil Store through Time Showing the Sequence i) Rainfall, ii) Drainage, iii) Soil water redistribution, and iv) Rainfall

This representation of the soil store generates direct runoff, according to the concept of a variable contributing area. Because the distribution of soil stores has an end member with zero storage capacity, some direct runoff will always be generated, even if all of the stores are empty, which corresponds to rain falling on the stream itself and the nearly saturated riparian zones. The contributing area expands as rainfall continues and contracts during periods of no rainfall. However, while it may be convenient to consider the distribution of stores to relate to an actual hillside profile, the formulation of the model does not specifically locate any stores within the catchment. It would be equally valid to assume that the soils with low storage capacity are those on the thin soils close to the watershed of the catchment. It is important to remember this when interpreting the results of the model application.

Incorporating evaporation makes this process slightly more complex. Potential evaporation was available as derived data from the AWS sites, and the most local site was used for each of the catchments modelled. When the soil as a whole is saturated, actual evaporation occurs at the potential rate; otherwise the actual rate is reduced by the ratio of actual soil water storage to the maximum soil storage capacity, so that, when the soil stores are empty, there is no evaporation.

In Moore's (1985) formulation of the model, the distribution of the stores is defined by a non-linear power-law function, but in this application the special case form of this function that defines a linear store distribution was found adequate. The water draining from the soil store is routed though a linear store representing deep soil/groundwater and is combined with the quick response runoff to produce total flow.

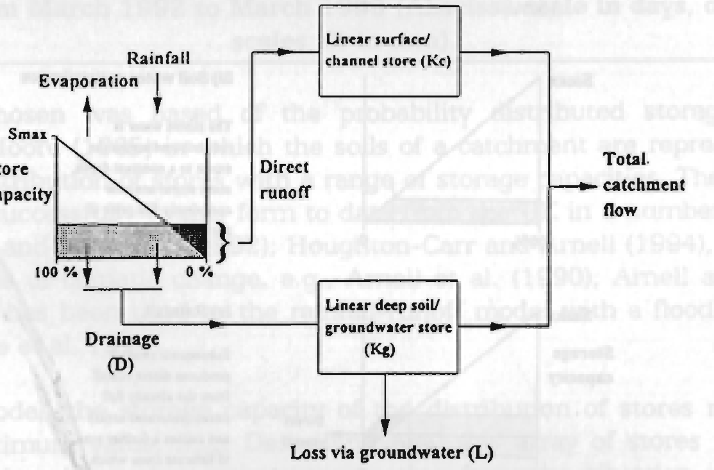

Figure 5: The Complete Rainfall-runoff Model Including the Probability Distributed Soil Store

However, an examination of the data shows that this model requires modification for these small Nepalese catchments. On the Chinniya, for example, rainfall was 4,970mm, compared with a total flow of 1,746mm and potential evaporation of 1,694mm, so that even if the potential evaporation was fully satisfied, 1,530mm (30%) of rainfall was 'lost' by some other process from the catchment. As actual evaporation will be less than the potential rate, the true losses will be even greater. While within the Bore and Bhandare catchments this loss could be through irrigation diversions on to flooded terraces, the Chinniya is a natural catchment with no such diversion, and the loss is most likely through groundwater leakage. This loss was represented in the model by a drain from the groundwater component of the model.

The resulting model contains five parameters: maximum soil storage, (S_{max}); soil store drainage rate, (D); storage constants for the channel and groundwater stores, (K_c and K_g); and the groundwater loss rate, (L)- the model is represented schematically in Figure 5.

The model was programmed within an interactive modelling shell that allows the goodness of fit to be assessed using both statistical measures and visual comparison. The statistical measure used in this case was an error sum of squares and an efficiency measure defined by Nash and Sutcliffe (1970):

$$\textbf{Efficiency} = 1 - \Sigma(Q_o - Q_s)/\Sigma(Q_o - Qbar)$$

where, Q_o is the observed flow, Q_s is the simulated flow, and *Qbar* is the mean of the observed flows. Using this measure, a perfect simulation has a value of 1. The graphical displays used to assess the simulations showed observed and simulated time series and flow duration curves.

The derived average potential catchment evaporation (PE), rainfall, and flow and simulated actual evaporation, soil water storage, and flow are shown in Figure 2 for the Chinniya catchment. As can be seen, there are several data errors in the flow and PE time series. The errors in the flows, most obviously the days when the observed flow drops to zero, can easily be ignored when inspecting the results visually. Missing PE data have been infilled with the average PE value, and these appear as the constant periods in the display. The rainfall data show no obvious errors, but comparison with the flow shows that, on some occasions, rainfall appears to show no associated flow response (e.g., at around day 205). The simulation successfully reproduces the observed onset of flow at the start of the two wet seasons and also the general magnitude of the larger peaks. During this simulation period, the soil store starts empty and reaches a peak saturation, in both wet seasons, of 60 per cent before completely emptying at the end of the wet seasons. The efficiency for the period shown in Figure 3 is 0.79.

The same model can be applied with reasonable success to the shorter periods of data available for the other two catchments with the adjustment of the two parameters defining the soil store, the maximum soil depth (S_{max}), and the drainage rate coefficient (D). The efficiency values for the Bhandare and Bore are 0.78 and 0.76, respectively.

The values of S_{max} are 314mm, 560mm, and 438mm for the Chinniya, Bore, and Bhandare catchments, respectively. The lower value for the Chinniya is physically realistic since it is located on thinner soils at higher elevations than the other catchments.

It is interesting to note that the simulations on the Bore and Bhandare show some underestimation of flows for a period of some two months at the end of the wet season; Figure 3 shows the simulation for the Bhandare. A possible explanation for this is that some of the 'lost' water is in fact stored on the catchment in the flooded terraces and is returned only slowly to the river channel.

Conclusions

Flow, rainfall, and other meteorological data have been collected and analysed to describe the climate and runoff regime of a number of small catchments in the Likhu *Khola*. The rainfall data allow a detailed description of local rainfall variability on an hourly basis. Establishing reliable and complete flow records proved more difficult, because of operation problems and uncertainty over defining good stage-discharge relationships for high flows.

Examination of the data together, and within the framework of a rainfall-runoff model, indicates that the catchments are almost certainly not watertight, and that a significant fraction of the water leaving the catchments does so as groundwater. By allowing for such a loss, the rainfall-runoff model was able to represent the general flow regime of the three catchments and, in particular, was able to represent the wetting-up at the beginning of the wet seasons before significant flow events can occur. Variations in model parameters between catchments were consistent with a simple physical classification of the catchments. On the two cultivated catchments, flows were maintained at the end of the wet season at higher levels than estimated by the model. It is unclear whether this is through a natural release of water stored within the soils or the result of man's conservation of water within flooded terraces for crop irrigation.

Further monitoring is needed to develop an understanding of the movement and storage of water within these catchments. This will bring direct benefits, as it will enable the efficient use of water for agriculture which is essential to maximise productivity. Other benefits will be a better appreciation of the risks to man that result from extreme flood and low flows. However, understanding water fluxes is also an essential first step in developing an understanding of the fluxes of dissolved and suspended material which is necessary to ensure the sustainable agricultural development of these catchments.

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