JOURNAL OF HYDROLOGY (N.Z.) Vol. 9, No. 2, 1970

A PRELIMINARY STUDY OF THE WATER BALANCE OF A SMALL CLAY CATCHMENT

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ABSTRACT

The catchment research undertaken on the River Ray, Buckinghamshire, U.K., is described in detail. Results from the first years of the investigation are presented in the form of a water balance which it is shown can be improved by the inclusion of a soil heat storage term.

INTRODUCTION

Although hydrology has developed more rapidly during the last decade than at any other time during its long history, it remains a science with few quantitative concepts (Crawford and Linsley, 1966). The considerable cost of basic research in the subject is one obstacle to progress. Another is that much of the effort has been devoted to producing practical solutions to particular problems, rather than on measuring and understanding the fundamental processes involved. These processes relate, of course, to components of the hydrological cycle, and one of the most satisfactory ways of studying them is by compiling a complete water balance for a watertight drainage basin or catchment. Then, by determining the quantity of water involved in each part of the cycle, not only can individual errors of measurement be detected more easily but also the relationships between the physical processes can be examined. Thus, the most satisfactory way of simplifying the behaviour of a catchment in terms of a general mathematical model can be found and the subsequent operation of this model for predictive purposes is less likely to be at variance with the real processes in the prototype.

There are, however, considerable scientific problems involved in making such a study. These arise in a number of ways: from the shortcomings of the existing instruments and techniques of measurement, from the difficulties of sampling and data collection, and from the intricacies of analysing the non-stationary time-dependent

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information that is produced (Ven te Chow, 1964). Nevertheless, a number of catchment studies have been undertaken, particularly in the United States, East Africa and South Africa, and more have been stimulated by the IHD programme for representative and experimental basins. The traditional approach has been to investigate the runoff characteristics of paired catchments before and after a change in land use on one of them. The effects of felling, grazing and various other treatments have been examined in this way, but criticisms have been made of these studies because they often employ measurements of only one or two of the components in the water balance. No experiments of this type were carried out in Britain until recently, but there have been a number of catchment studies not involving a land-use change. The earlier ones were conducted by McClean (1927, 1935) employing measurements of only rainfall and runoff. Since the work on the Stour (Penman, 1950) where potential evaporation estimates were used, there have been several more complete studies (Howe and Rodda, 1960; Smith, 1965). One such study is being undertaken in the area around the

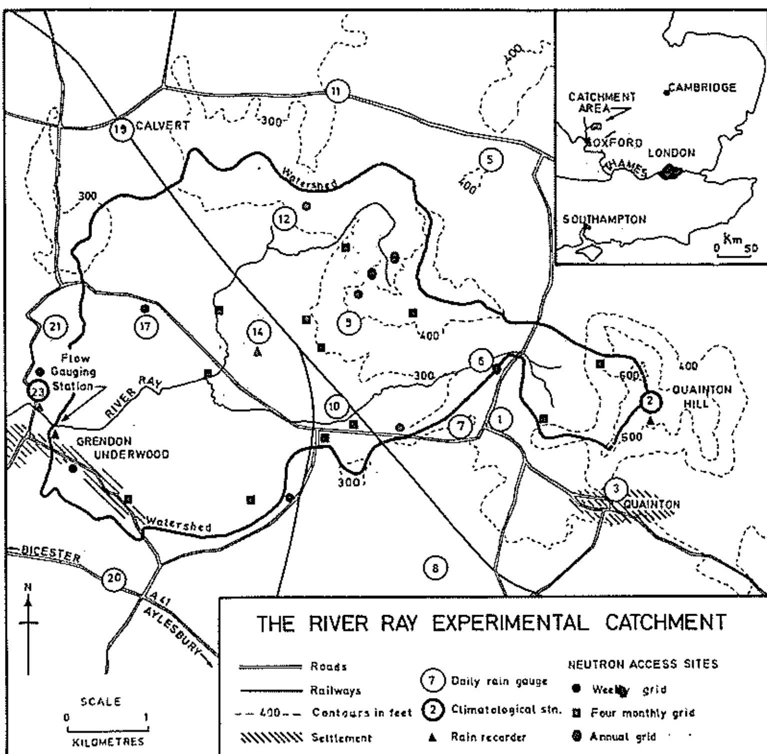


FIG. 1 — Location and instrumentation of the River Ray catchment.

headwaters of the River Ray in North Buckinghamshire (Fig. 1), with the main objective of devising a rational method for forecasting the discharge from that catchment (Nash and Sutcliffe, 1970).

PHYSICAL BACKGROUND

The headwaters of the River Ray drain an area of 1856 hectares (7.17 square miles) up stream from Grendon. With the exception of Quainton Hill (Fig. 2), the entire catchment is composed of clay which reaches a depth of over 30.5 m (100 ft) in the north-west corner. The presence of the clay and its apparent water-tightness was one of the main reasons for selecting this area, others being the existence of a clearly defined watershed and proximity to the Insitute of Hydrology at Wallingford.

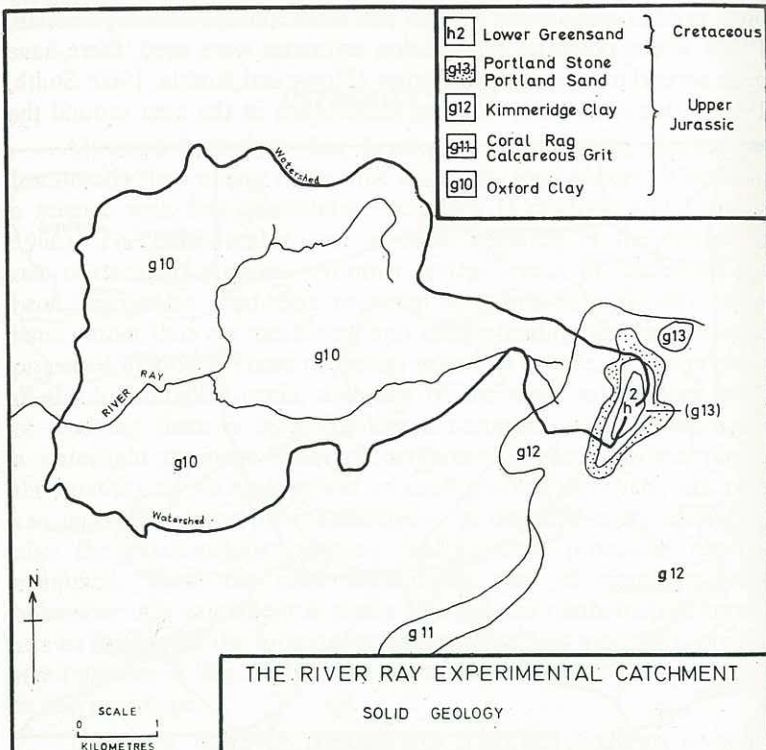


FIG. 2 — Solid geology map.

The hills that form the northern watershed have a thin covering of Glacial Drift. There is some Head towards the centre of the catchment, but the southern boundary is free from such deposits. As a result there is a gradation from the heavy stone-free Oxford clay-derived soils of the south, to those of a somewhat lighter nature in the north. The weather and climate of the area are typical of central England. Average temperatures range from a January mean of 4.4°C (40°F), to 16.7°C (62°F) in July, while the average rainfall is about 660 mm (26 in.) with little snow. Some 460–490 mm (18 to 19 in.) of evaporation takes place in most years, but because of the fairly even distribution of rainfall throughout the year, a soil moisture deficit occurs each summer and the river usually runs dry.

Vegetation in the catchment is mainly short grass (70%) with some areas of woodland and arable farmland. Water supplies are piped from outside the area to the village of Grendon Underwood, while most of the domestic drainage is taken out of the catchment.

INSTRUMENTATION

Because of the apparent absence of ground water, instruments were installed to measure a surface water balance (Fig. 1). The storage changes that do take place are considered to occur close to the surface. mainly in the root zone. Hence soil moisture content was measured to estimate these changes, together with precipitation, runoff and potential evaporation.

At some 20 sites volunteers take daily observations of rainfall using standard rain gauges (Meteorological Office Mk. II, 30.5 cm high, 12.5 cm diameter), while one site has a standard gauge installed with its rim at ground level inside a non-splash surface (Rodda, 1967a). Three of the sites are equipped with autographic rain recorders fitted with a special strip chart mechanism, while two other sites have had autographic gauges for part of the study period. The availability of volunteer observers determined the spatial form of the rain-gauge network, rather than the requirements of any objective technique, but in the event a fairly uniform cover was achieved.

Although stream-gauging structures have been planned for several points on the River Ray, only one has been built and operated. This is at the main outfall from the catchment, where a critical-depth trapezoidal flume (Ackers and Harrison, 1963) was constructed in 1962. Originally this structure had a capacity of 5.5 m^3/s (200 cusecs), but following a flood which submerged it, the walls of the flume were raised to increase its upper limit to 8.5 m^3/s (300 cusecs). This was thought to correspond to a flood of about a 10-year return period. For the first year, the flume was equipped with a single water-level recorder, but this was replaced by a more accurate instrument supplemented by a punched-tape water-level recorder. Another apparatus, which is connected to the public telephone system, can be interrogated for the current water level. A check was maintained on the flume zero, initially by careful levelling, but more recently by using a manometer device (Hydrological Research Unit, 1967) which can detect errors of as little as 0.3 mm (0.001 ft).

Two climatological stations are operated as part of the study, one at either end of the catchment. At the western station (site 23) daily observations are made of all the elements necessary for estimating potential evaporation and transpiration. There is also an evaporation pan and two irrigated drainage lysimeters at this site. The second station is visited weekly so that charts on the recorders can be changed and instruments re-set, including the special cup counter anemometer (Key, 1965) that was developed for this type of site.

At the start of the experimental work 12 sites were instrumented for the assessment of soil moisture change, each chosen as being representative of a particular soil type. Electrical resistance units, made from nylon and stainless steel, were installed at each site at six depths from 15 cm (6 in.) to 168 cm (5 ft 6 in.) through the profile. These installations have since been replaced by access tubes used for the neutron-scattering method of measurement (Bell and McCulloch, 1966).

The present network consists of access tubes at eight of the original sites, and these are read weekly at eight depths between 10 cm (4 in.) and 150 cm (4 ft 11 in.). This primary network is supplemented by a more extensive one of 16 extra tubes, which is read four or five times a year at carefully chosen intervals, when it is thought that the major part of the water stored in the catchment is contained in the soil. In addition, there are two recently established woodland networks of 30 and 40 tubes on a close-gridded system, which are used to interpret the soil moisture changes under trees.

Apart from the regular weekly readings, there have also been intensive samplings at some 25 to 35 sites at the beginning of each water year (1 October), using screw auger and core samples for soil moisture determination by the gravimetric method. These sampling exercises have been discontinued, however, and replaced by observations from the extensive network of access tubes.

Investigations are being made into the movement of water through the clay to test its supposed watertightness. The technique of dating soil water by tritium analysis is being used and results, so far, have not indicated that there is movement below 2 m (6 ft 6 in.). In fact they show that the seasonal cycle of recharge and abstraction takes place above this level (Smith *et al.*, 1970). Other techniques are to be used to prove whether or not there is deep percolation through the clay, but it is expected that these will confirm the initial assumption that there is no measurable loss to the underlying strata.

DATA PROCESSING AND ANALYSIS

Data are collected in various forms from the catchment. Some consist of single readings at set times, some are totals integrated over periods of an hour or a day, and others are continuous records on strip charts or punched paper tape. All the data are collated and subjected to simple checks designed to eliminate gross errors and gaps in records. Most of the data are then transferred to punched cards and put through a system of quality control (Mandeville *et al.*, 1968).

The system consists of three distinct stages: firstly, the raw data on cards are submitted to a simple accounting procedure which checks for and locates punching errors and spurious values. Secondly, the corrected data are assembled by computer on magnetic tape to enable large quantities of data to be handled in a single run. This tape is known as the 'copy tape' and is employed in the subsequent calculations of mean basin rainfall, potential evaporation and discharge, for the smallest time interval consistent with the quality of the data and the method of calculation. Finally, the computed data are assembled chronologically on a final tape, called the 'punched tape', which can be used in water-balance and mathematical-model work.

Mean basin rainfall is obtained from the daily standard-gauge totals together with the adjusted hourly amounts from the chart recorders. Each standard gauge is assigned to the nearest recording gauge and its daily total divided into hourly amounts according to the distribution of rainfall on the chart record. These values are then used to assess the basin mean, hour by hour, by the Thiessen polygon method. Using the same polygons, basin rainfall is also calculated on a daily basis from the punched cards and monthly means are determined by the isohyetal method. These latter values closely match the hourly estimates totalled over the appropriate period and provide an independent data quality check.

Stream discharge is calculated from the stage records on the copy tape using the flume calibration stored in the computer. Total daily flows and instantaneous discharge are computed at intervals dependent upon the rate of change of the hydrograph and transferred to the processed tape. The punched paper tape records from the auxiliary recorder are employed in separate calculations of daily flow, and the two sets of values are then compared for anomalies.

Potential evaporation and transpiration are calculated on a daily basis from the combination of bulk aerodynamic and heat-budget techniques after the method of Penman (1948, 1956, 1962). The computer programme used in evaporation estimation incorporates some of the features of previous programmes and tables (Berry, 1964; McCulloch, 1965) and accepts a variety of input data in British or metric units.

THE WATER BALANCE

The success of any analysis and interpretation of the catchment data may depend ultimately on the accuracy of the measurements of individual components of the hydrological cycle. The level of absolute accuracy cannot be assessed because of the inadequacies of the sampling techniques used for rainfall and soil moisture determination and the use of semi-empirical methods for evaporation estimation. By drawing up a water balance, however, the

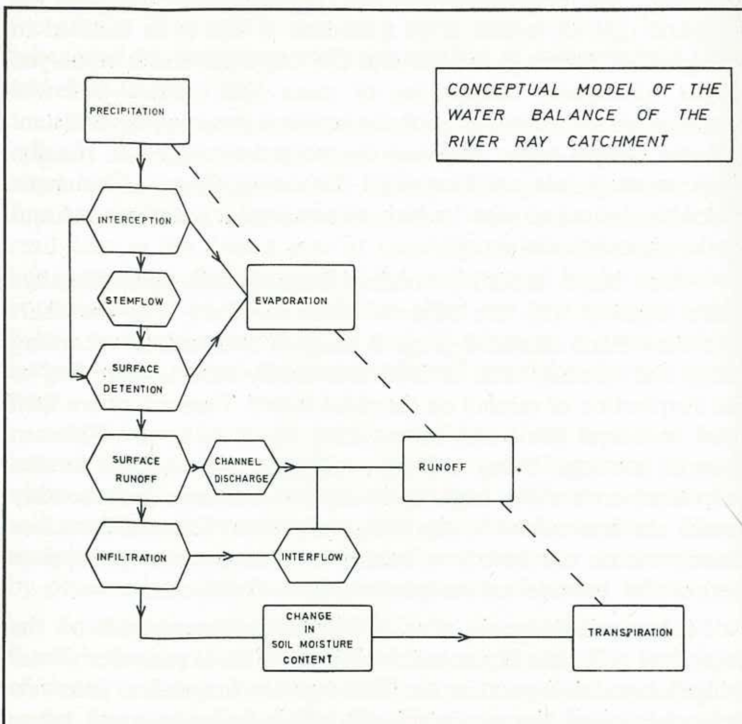


FIG. 3 — Conceptual model of the water balance of the River Ray.

relative accuracy of the data can be inferred from the level of cumulative imbalance over a period of time, provided that there are no compensating errors.

A conceptual model of the water balance for the River Ray catchment is given (Fig. 3) but the relations between the major components can be stated more simply as:

$$\Delta S = P - (Q + E)$$

where ΔS = storage changes taking place during a given period

P = mean basin precipitation for the same period

Q = runoff for the same period

E = mean basin actual evaporation and transpiration for the same period

The storage changes calculated from this equation can be compared with the measured changes in soil moisture. As a first approximation, use can be made of the fact that the catchment is not getting progressively wetter or drier over the years. The variations in ΔS are shown on a weekly basis for the period January 1964 to October 1968 (Fig. 4) for different combinations of standard and ground-level rainfall measurements (Rodda, 1967b) and estimated potential transpiration values from two versions of the Penman formula. Rainfall was corrected to ground level by applying the relationship between standard and ground-level catches that was found for one site, to all sites in the network. It was also assumed in the calculation of potential transpiration that the albedo for grass (0.25) applied to the whole catchment for the whole year, rather than some other value weighted to account for the different albedos and the small areas of other crops and woodland they typify. It can be seen that the most sensible picture is obtained for ground-level rainfall and Penman 1962 potential transpiration values. Other combinations result in such a rapidly decreasing catchment storage that their use would be clearly inappropriate.

In these graphs, the different regimes from year to year are readily apparent and, in particular, the exceptionally dry character of 1964 is well marked. The long-term balance shown by these graphs, however, masks the seasonal discrepancies which are a feature of week-by-week comparisons. The storage changes measured by the neutron scattering method are shown in comparison with those calculated from the daily water balance (Fig. 5). There is a striking seasonal imbalance, the calculated storage exceeding the measured storage in winter and falling well below it in summer. An arbitrary datum has been chosen for the soil

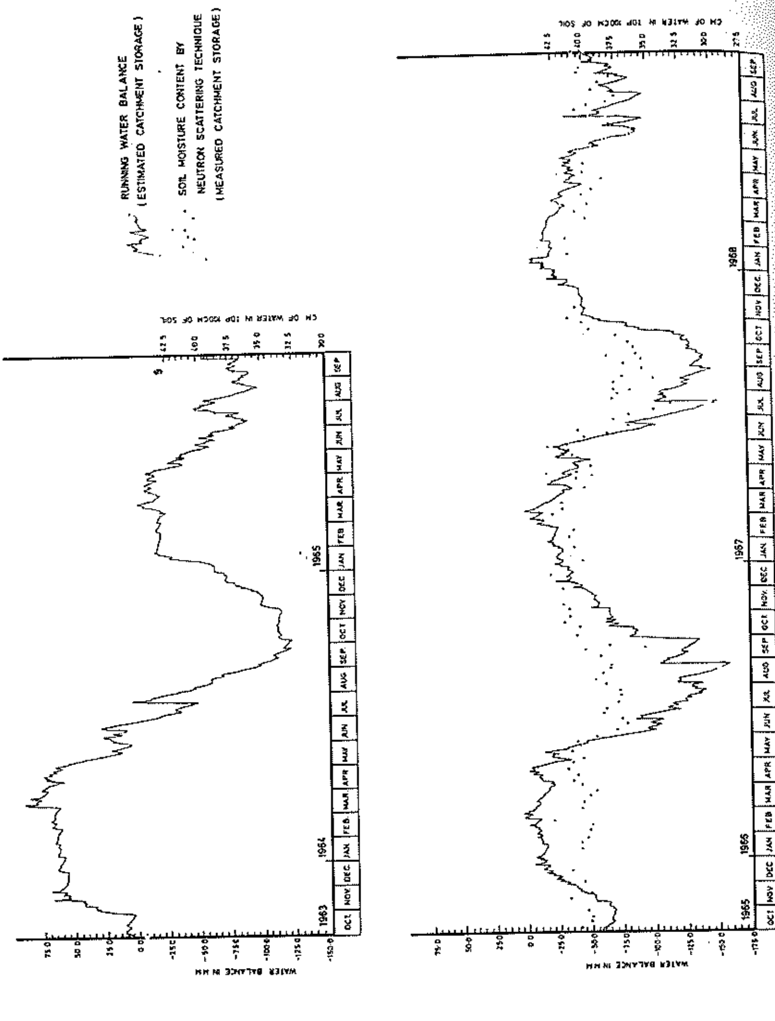


FIG. 4 — Weekly cumulative water balance.

moisture values, but the seasonal discrepancies are not dependent upon it. If such large differences are not due to systematic errors in the soil moisture measurements, and it seems most unlikely that they are, then it is apparent that corrections of rainfall, runoff or evaporation will affect the water balance graphs in Figure 4 and any conclusion drawn from them. It is important, therefore, to attempt to detect the source or sources of this apparent seasonal imbalance.

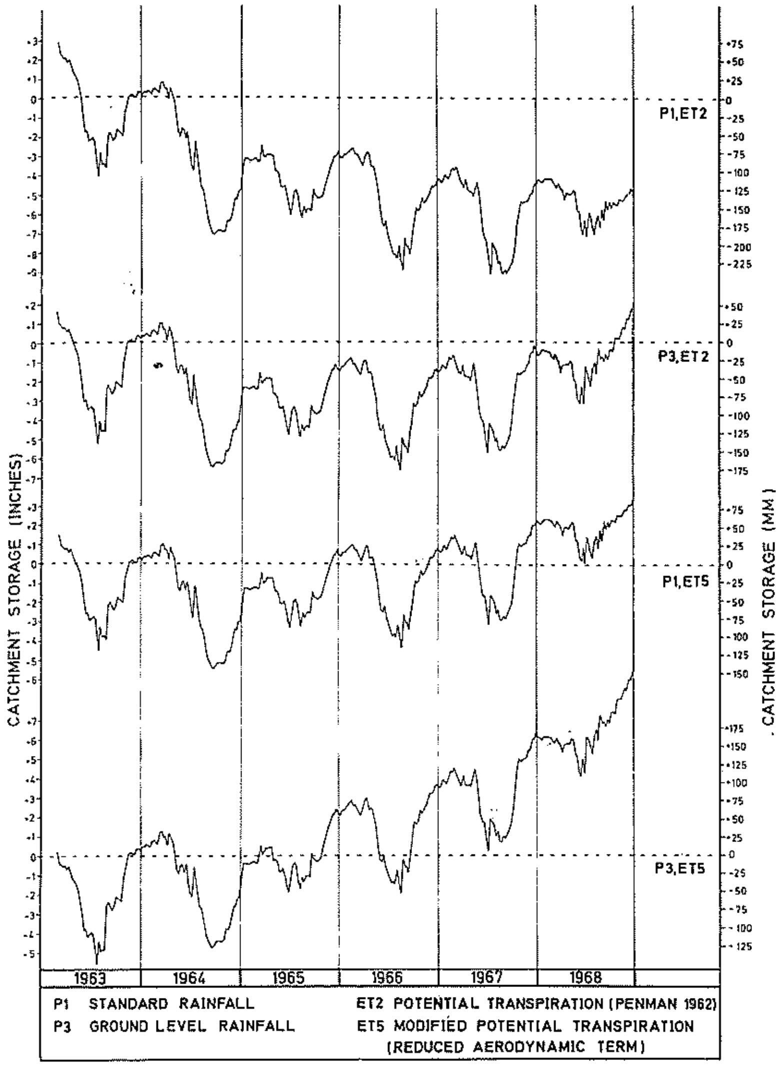


FIG. 5 — Measured and calculated catchment storage.

There are many sources of accidental and systematic errors which can affect the water balance (Fig. 6). Most of these, however, can be eliminated because they are insignificant in terms of this large imbalance ± 50 mm (2 in.), or because they apply in one direction only. There are unknown errors due to the conversion of point measurements to areal estimates, due to surface storage of water in winter, and due to volume changes in the clay during the wetting and drying cycle. There is also the possibility of some bias being introduced into the mean soil moisture values which can be attributed to the original sampling network. All these factors are being examined to assess their effect on the water balance, but it is strikingly apparent that small changes in the estimates of potential evaporation or transpiration could easily rectify the seasonal imbalance. In addition, errors could arise owing to the assumptions basic to the Penman method not being applicable. These are: that the transfer coefficients for water vapour and heat are identical, that the evaporating surface is saturated at the temperature of the surface, that the aerodynamic term is valid for the surface in question, and that advective heat energy and heat storage in the surface are negligible quantities.

On the other hand, considerable experimental evidence exists (Rider and Robinson, 1951; Crawford, 1965; Dyer and Swinbank, 1967), which demonstrates the near equality of the transfer terms under a wide range of atmospheric conditions. Thus the first assumption no longer depends on the frequency of neutral or near-neutral stability, as was implied by earlier work (Pasquill, 1949).

The second assumption, however, is known to be frequently not satisfied in the case of a crop-covered surface. Under these unsaturated conditions, the third assumption is also not valid (Deacon *et al.*, 1958). In addition, the aerodynamic term may be generally inapplicable for vegetation of roughness length greater than short grass (Businger, 1956; Tanner and Pelton, 1960). Several workers have attempted to use less empirical aerodynamic terms, which incorporate measures of the roughness length and stomatal resistance of the plant cover. In the case of short grass, with a low stomatal resistance and an aerodynamically smooth surface, it is unlikely that serious errors of the magnitude of those referred to above are introduced by the omission of such corrections.

Advective heat energy has been shown to reach significant proportions (McIlroy and Angus, 1964) and the well known 'oasis' effect is a manifestation of this addition to net radiation. Tanner and Pelton (1960) state that the Penman formula appears to account for advective heating and, under British climatic conditions and a short crop cover, it is assumed that further errors introduced by this effect are of a minor nature.

The heat storage term, on the other hand, is usually neglected on the grounds that the net daily flow to and from the soil is small in comparison with the net radiation. Over long periods of a season or a year, however, there is much less justification for ignoring this

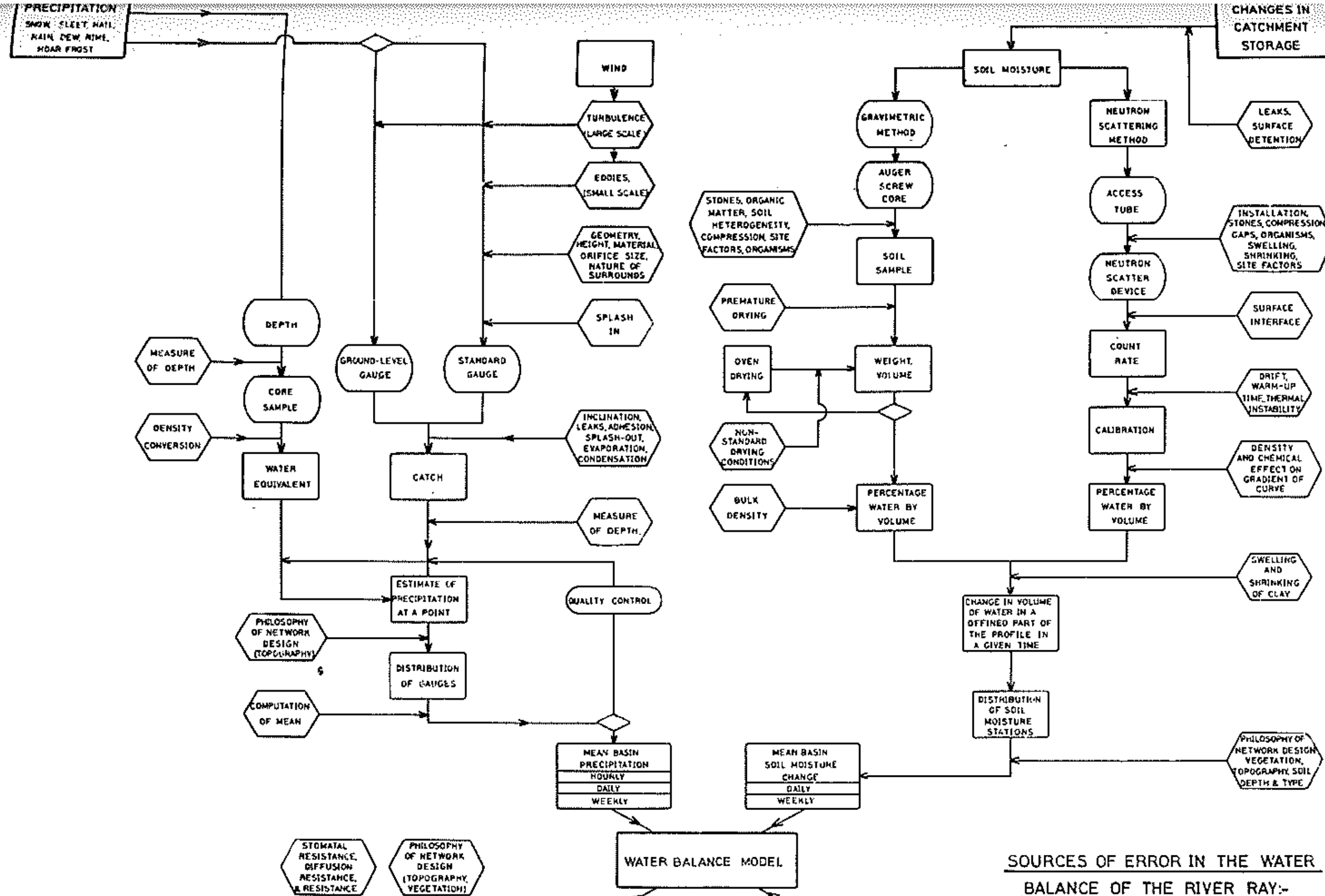
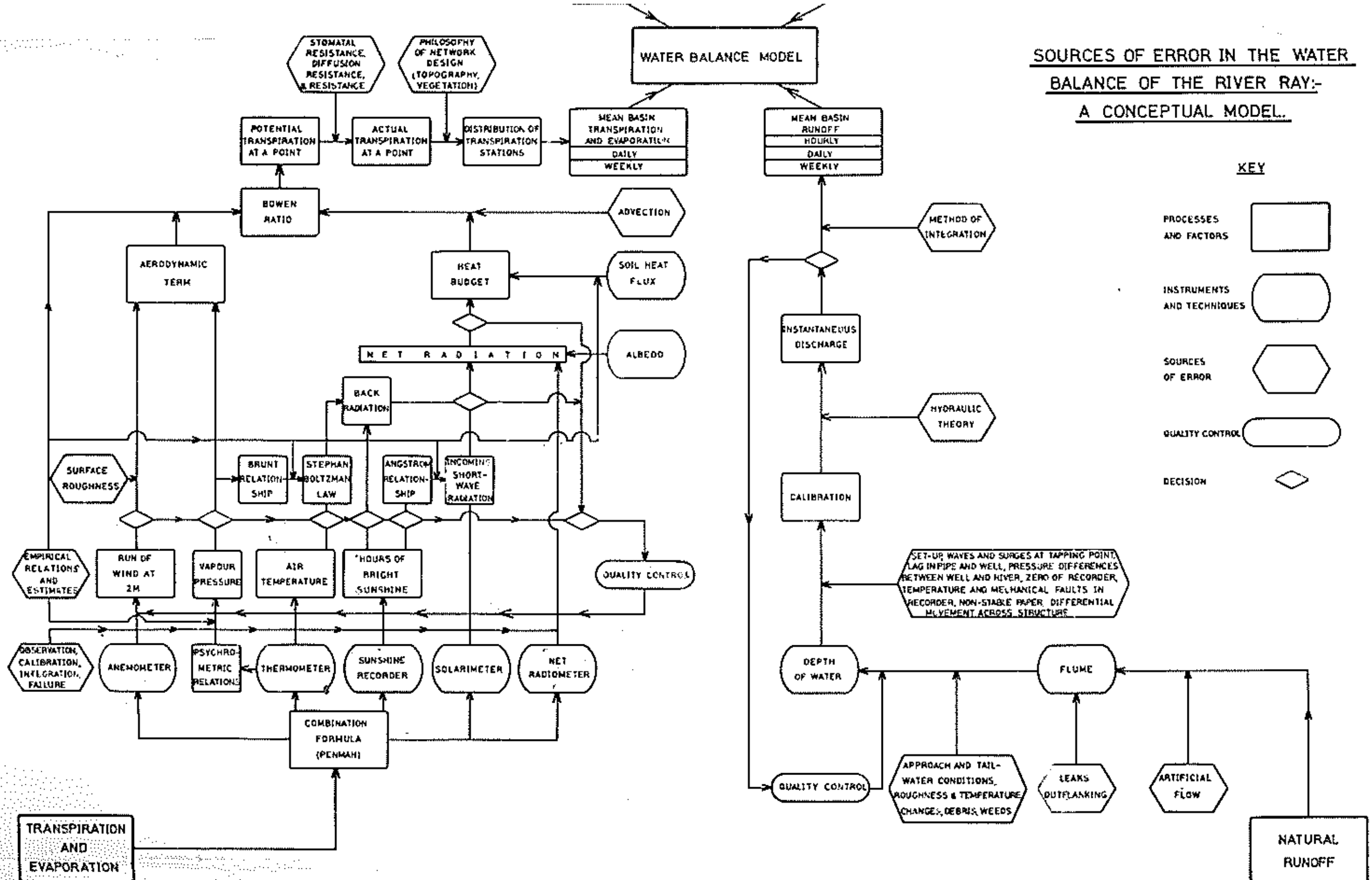


FIG. 6 — Sources of error in th

rror in the water balance.

SOURCES OF ERROR IN THE WATER BALANCE OF THE RIVER RAY:- A CONCEPTUAL MODEL.



factor. McIlroy and Angus (1964) have found large heat storage effects reaching a maximum water equivalent of 0.25 mm/day in April and October. Aslyng (1965) shows that the average seasonal heat storage in a Copenhagen soil during the period 1955–65 can approach ± 50 mm. This amount is clearly of the right order of magnitude to account for a considerable part of the seasonal imbalance, even allowing for not all of the energy being available for evaporation. The mean Bowen ratio, obtained from the Copenhagen data, indicates that at least 85% of this energy would be available for evaporation.

In addition to the above source of error, there is, of course, the problem of the effect of an increasing soil moisture deficit on the rate of transpiration. Under the conditions encountered in the River Ray catchment during the period of study, only in 1964 is there a clear fall from the potential rate. That is not to say that a smaller reduction does not occur in the other years, but until the effects of soil heat storage are eliminated from the water balance, it is not possible to separate these influences. One thing is clear from Figure 4. If the rate of actual transpiration is significantly lower than the potential rate in the summers 1965 to 1968, then the estimates of potential transpiration from Penman's 1962 formula are much too low for the winter period of the year.

HEAT STORAGE IN THE SOIL

Neglect of a soil heat storage term appeared to be the most probable source of error in the estimate of evaporation. Hence an attempt was made to assess seasonal changes in heat storage from standard soil and earth thermometer records from one site in the catchment (site 23). Temperature, moisture and density profiles were constructed on days when there were soil moisture measurements which had been preceded by at least four days without rain. On these occasions, soil moisture was regarded as being a good measure of catchment storage. The thermal capacity of the soil was calculated and integrated over the profile to the lowest depth where temperature records were available (122 cm, 4 ft). The annual cycle of temperature variation was assumed to reach a depth of 6 m (20 ft) and a linear extrapolation was used to calculate that part of the exponential temperature profile below 122 cm. From any two profiles the amount of heat gained or lost was calculated and plotted against the difference between the Penman estimates and the transpiration values calculated from the water-balance equation (Fig. 7).

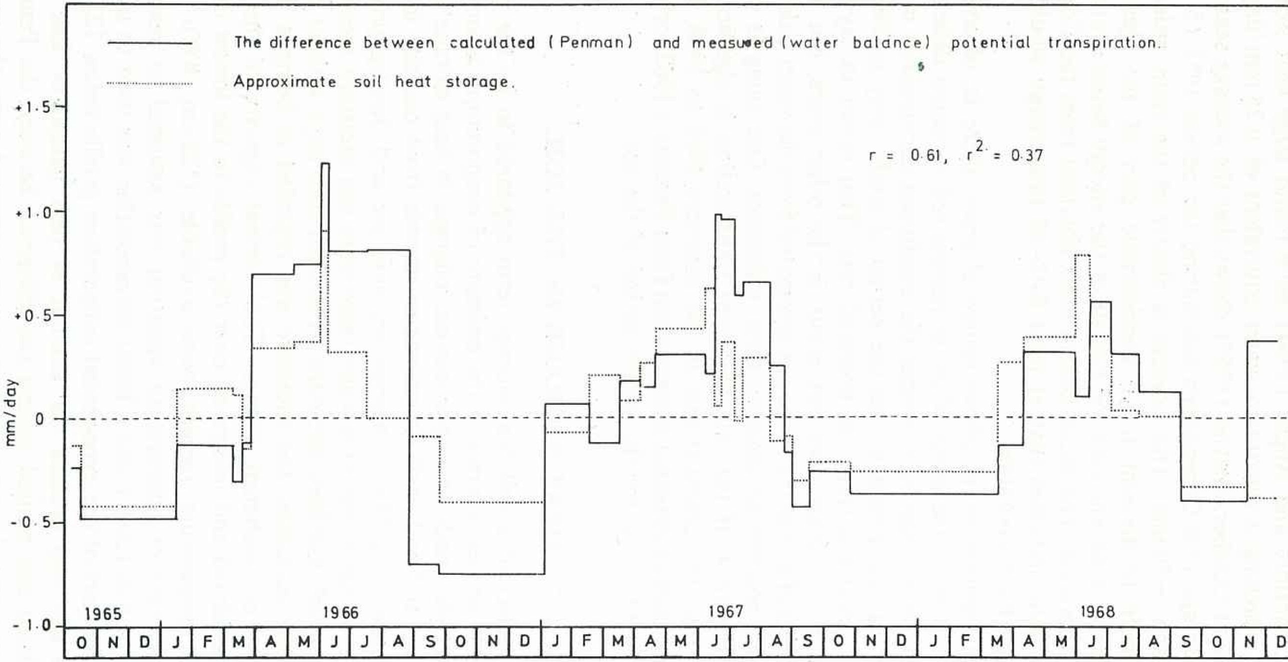


FIG. 7 — Soil heat storage.

While there are still large quantities to be accounted for, it is clear that a correction based on heat storage in the soil would remove much of the difference between measured and estimated catchment storage. For the data available up to the end of 1968, a correlation coefficient of 0.61 was obtained between this difference and the soil heat storage determined for 35 periods defined by the soil moisture records. The discrepancies in magnitude between these amounts must be due largely to the coarseness of the technique employed for assessing the soil heat flux. In contrast, there appears to be a good agreement in phase between the two quantities. Refinement of the method of determining the soil heat flux will doubtless lead to an improved relationship.

CONCLUSION

The first catchment studies were begun more than 50 years ago and there are now several hundred in progress in different parts of the world, yet this approach to hydrological problems has been severely criticised on grounds of high cost, the long period required for data collection, the frequently poor quality of the data, and the difficulty of extrapolating the results to other areas (Slivitzsky and Hendler, 1964; Ackerman, 1966; Reynolds and Leyton, 1968).

On the other hand, catchment research continues to offer advantages that plot studies, meteorological methods and the similar alternatives lack in the securing of basic knowledge of hydrology. Not only does it allow an assessment of the precision of measurement through a compilation of a water balance, but also it allows the inclusion in models of the hydrological cycle significant components which might otherwise have been omitted.

In this study of a physically simple catchment, it has been shown that systematic errors arise from the use of the Penman formula to estimate potential evaporation. These errors could be as much as 100 mm (4 in.) in the estimation of water use between the months of March and September. While it is true that more stringent reductions in potential transpiration with increasing soil moisture deficit are often advocated, it is difficult to see how long-term imbalance is to be avoided without a compensating increase in the winter rates of evaporation.

As a result of the water balance analysis it was concluded that these errors arise in part from the omission of a soil heat storage term. This was verified by the estimation of soil heat storage from soil temperature records. Future work in this catchment study is designed to resolve some of the remaining problems of measurement and sampling and to improve the water balance further.

The need for careful measurement at every stage in the hydrological cycle is apparent but, with the large measure of success in the water balance of the River Ray, the viability of catchment research on this scale is successfully demonstrated. Indeed, as Hewlett *et al.*, (1969) conclude, the method is sound and its future in any comprehensive research programme is secure.

ACKNOWLEDGMENTS

The authors wish to thank the large number of individuals and organizations that have contributed towards this study. These include the Thames Conservancy, H.M. Prison Commission, the Soil Survey, the Meteorological Office, the London Brick Company and the volunteer observers who take rainfall readings. They are also indebted to their colleagues for the effort and skill they put into this study.

REFERENCES

Ackerman, W. S. 1966: *Guidelines for research on hydrology of small watersheds.* Office Water Resources Res., U.S. Dept Interior, Washington, D.C. p. 26.

Ackers, P.; Harrison, A. J. M. 1963: *Critical depth flumes flow measurement in open channels.* Hyd. Res. Paper 5, Hydraulics Research Station. H.M.S.O.

Aslyng, H. C.; Jensen, S. V. E. 1965: Radiation and energy balances at Copenhagen 1955–64. *Yearbook 1966.* Royal Veterinary and Agricultural College, Copenhagen. pp. 22–40.

Bell, J. P.; McCulloch, J. S. G. 1966: Soil moisture estimation by the neutron scattering method in Britain. *J. Hydrol. (Neth.) 4*: 254–263.

Berry, G. 1964: The evaluation of Penman's natural evaportion formula by electronic computer. *Aust. J. appl. Sci. 15*: 61–64.

Businger, J. A. 1956: Some remarks on Penman's equations for the evapotranspiration. *Neth. J. agric. Sci. 4*: 77–80.

Crawford, N. H.; Linsley, R. K. 1966: *Digital simulations in hydrology, Stanford Watershed Model IV.* Tech. Rept 39, Stanford Univ. Dept Civ. Eng., Stanford, California. p. 221.

Crawford, T. V. 1965: Moisture transfer in free and forced convection. *Quart. J. roy. Met. Soc. 91*: 18–27.

Deacon, E. L.; Priestley, C. H. B.; Swinbank, W. C. 1958: Evaporation and the water balance. *UNESCO Arid Zone Research, 10. Climatology.* pp. 9–34.

Dyer, A. J.; Swinbank, W. C. 1967: Turbulent transfer of heat and water vapour in an unstable atmosphere. *Quart. J. roy. Met. Soc. 93*: 501–508.

Hewlett, J. D.; Lull, H. W.; Reinhart, K. G. 1969: In defence of experimental watersheds. *Wat. Resources Res. 5*: 306–316.

Hydrological Research Unit 1967: *Record of Research 1967*. H.M.S.O.

Howe, G. M.; Rodda, J. C. 1960: An investigation of the hydrological cycle in the catchment area of the River Ystwyth during 1958. *Wat. and Wat. Eng. 64*: 10–16.

Key, M. T. H. 1965: A weekly recording anemometer. *Met. Mag. 94*: 113–114.

Mandeville, A. N.; Plinston, D. T.; Hill, A. 1968: *Processing errors in the analysis of catchment data.* Institute of Hydrology, Report No. 5. Wallingford, Berks., U.K.

McClean, W. N. 1927: Rainfall and flow-off in the River Gary, Inverness-shire. *Trans. Inst. Wat. Engrs 32*: 110.

McClean, W. N. 1935: River flow records: River Dee, Aberdeenshire. *Quart. J. roy. Met. Soc. 61*: 433.

McCulloch, J. S. G. 1965: Tables for the rapid computation of the Penman estimate of evaporation. *E. Afr. agric. for. J. 30*: 286–295.

McIlroy, I. C.; Angus, D. E. 1964: Grass, water and soil evaporation at Aspendale. *Agric. Met. 1*: 201–204.

Nash, J. E.; Sutcliffe, J. V. 1970: River flow forecasting through conceptual models, Part 1, A discussion of principles. *J. Hydrol. (Neth.) 10*: 282–290.

Pasquill, F. 1949: Some estimates of the amount and diurnal variation of evaporation from a clayland pasture in fair spring weather. *Quart. J. roy. Met. Soc. 75*: 249–256.

Penman, H. L. 1948: Natural evaporation from open water, bare soil and grass. *Proc. roy. Soc. London (A) 193*: 120–145.

Penman, H. L. 1950: The water balance of the Stour catchment area. *J. Inst. Wat. Engrs 4*: 457–469.

Penman, H. L. 1956: Evaporation — an introductory study. *Neth. J. agric. Sci. 4*: 9–29.

Penman, H. L. 1962: Woburn irrigation 1951–1959. *J. agric. Sci. 58*: 343–379.

Reynolds, E. R. C.; Leyton, L. 1967: Research data for forest policy; the purposes, methods and progress of forest hydrology. *9th Brit. Comm. For. Conf.*

Rider, N. E.; Robinson, G. D. 1951: A study of the transfer of heat and water vapour above a surface of short grass. *Quart. J. roy. Met. Soc. 87*: 375–401.

Rodda, J. C. 1967a: The rainfall measurement problem. *Proc. Berne Assembly of the I.A.S.H.* pp. 215–231.

Rodda, J. C. 1967b: The systematic error in rainfall measurement. *J. Inst. Wat. Engrs 21*: 173–177.

Slivitsky, V. E.; Hendler, M. 1964: Watershed research as a basis for water resources management. *Fourth Canadian Hydrol. Symp.* National Research Council, Canada. p. 10.

Smith, K. 1965: Rainfall runoff and water balance in Nidd Valley, Yorkshire. *Wat. and Wat. Eng 69*: 5–10 .

Smith, D. B.; Wearn, P. L.; Rowe, P. C. 1970: Water movement in the unsaturated zone of high and low permeability strata using natural tritium. *Sym. on use of Isotopes in Hydrol.* I.A.E.A., Vienna.

Tanner, C. B.; Pelton, W. L. 1960: Potential evapotranspiration estimates by the approximate energy balance method of Penman. *J. Geophys. Res. 65*: 3391–3413.

Ven te Chow 1964: *Handbook of Applied Hydrology*. McGraw Hill, New York.