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THE INFLUENCE OF CHANGING LAND USE OF INFLOW TO RESERVOIRS

DEUR/BY:

J.S. WHITMORE, P.C. REID

AFDELING/DIVISION:

HYDROLOGICAL RESEARCH INSTITUTE

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SUMMARY

A technique has been developed for assessing the significance of time trends in run-off per unit of rainfall. When applied to the records of 50 gauging stations in South Africa the method revealed a marked predominance of downward trends. In general, the higher the mean annual rainfall, the greater is both the percentage and the absolute reduction in run-off as a function of time. As there is no evidence of any large-scale, long-term change in the incidence of rainfall, the trends are doubtless attributable to intensified soil and water conservation measures and changes in land use. The results of the analysis highlight the necessity of examining all run-off records for trends, and adjusting them accordingly, so as to arrive at realistic estimates of current and projected mean annual run-off which is such a crucial factor in the economic design and efficient operation of a large dam.

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QUESTION 47

THE INFLUENCE OF CHANGING LAND USE ON INFLOW TO RESERVOIRS(x)

JOAN S. WHITMORE, M.A. AND P.C. REID, B.Sc(AGRIC).

DIRECTOR AND SENIOR HYDROLOGIST,
HYDROLOGICAL RESEARCH INSTITUTE, DEPARTMENT OF WATER AFFAIRS
SOUTH AFRICA

INTRODUCTION

A crucial environmental factor affecting dams and reservoirs is the extent to which changing land use diminishes and alters the characteristics of the run-off from catchments. This paper presents the results of analyses of the conditions in some South African catchments.

It is commonly accepted that the mean annual run-off from the land area of the Republic of South Africa, including the Lesotho and Swaziland enclaves, is about 52 000 million m³ (8,1 per cent of the mean annual rainfall). Of this, on average about 21 000 million m³ a year could be harnessed for use if sufficient storage were provided. The contribution of groundwater to the potential supply has been conservatively assessed at about 1,100 million m³ a year; a large percentage error in estimating this small component would not materially affect the overall issue.

Turning to water demands, it has been estimated that if the current annual increase of about 2 per cent in

(x) L'influence des changements de l'utilisation des terres sur les eĉoulements dans les reservoirs.

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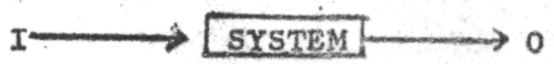
in balance.

That is

$$I - O = \Delta S$$

where I = input (water entering the sub-system)
O = output (water leaving the sub-system)
ΔS = change in storage within the sub-system

Schematically,

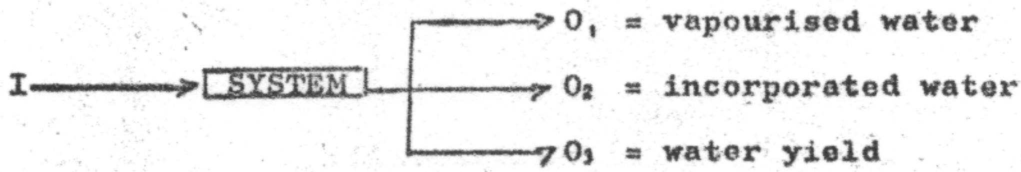


where I = input
= precipitation falling on the system + surface inflow + subsurface inflow + imported water

ΔS = change in the quantity of water stored within the system

O = output
= surface outflow + subsurface outflow + vapourised water + water incorporated in products leaving the system + exported water

For an independent catchment this would be tantamount to



Proceeding to a further degree of refinement,

$$I = O + \Delta S$$
$$= O_1 + O_2 + O_3 + \Delta S$$
$$= (e + t) + O_2 + (s + g) + \Delta S$$

where I = input
O = output
O_1 = vapourised water
= $e + t$

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where e = evaporation

t = transpiration

O_2 = water incorporated in products leaving the catchment

O_3 = water yield

= s + g

where s = surface water yield

g = groundwater yield

ΔS = change in storage

O_3, representing what is commonly denoted by the term "water resources", together with O_2 (generally much smaller) can be regarded as potentially "productive" water, in con= trast to O_1 which can be deemed water "loss".

To maintain the hydrological equilibrium, a change in any term(s) must effect a compensating change in one or more of the other terms.

It follows that the water yield, O_3, can be influenced, jointly or severally, by

- a change in input, especially in precipitation, and/or by
- such changes in the system through which the water is routed as can alter the apportionment between the "loss" and "yield" terms.

In a stable system with an established relationship between O_1 and O_3, both are largely predictable in terms of I. Thus, for an agricultural catchment that has an established mode or pattern of land use, is geomorphologi= cally fairly stable and has no major storage or diversion works, both "loss" (O_1) and "yield", i.e. water resources (O_3), are directly a function of rainfall input and associated climatic factors. But, induce a change within the system through which the input is routed - for example, by converting short, shallow-rooted grassland to tree plantations - and a permanent change in the quantitative

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relationship between the "loss" and "yield" terms will likely ensue, as well as an alteration in the time distribution of the yield. Changes in the system may also affect the quality of the water yield.

Generally, the longer water is retained within the system, the greater are the vapour "losses", and these proceed at the expense of water yield.

INTERACTIONS WITHIN THE HYDROLOGICAL SYSTEM

This elementary incrusion into system dynamics is merely intended to stress that a change in any term(s) in the hydrological equation will of necessity induce a compensating effect on one or more of the others, and that in respect of run-off and groundwater recharge such trends may be lasting. The change may also be radical for, while the compensation will be equal but opposite in absolute terms, disparity in the quantities of water involved in the various phases of the hydrological cycle implies that a seemingly negligible change in a major component of the cycle will induce a far greater relative change in a minor component. For example, assume the mean annual rainfall over catchment X to be 500 mm of which 45 mm runs off, and that a change in land use reduces run-off by 15 mm. The increase in retention is a mere 3 per cent whereas run-off is reduced by 33 per cent - and it is the run-off that is of concern to the dam builder.

STATISTICAL TRENDS IN THE RAINFALL/RUN-OFF RELATIONSHIP

Particularly since World War II there has been a marked intensification in agricultural production and in soil and water conservation measures. Urban and industrial development has likewise been phenomenal. All these activities affect not only use of water but also supply. Let us consider each in turn.

A trebling over the past 30 years of the index representing the volume of agricultural production is indicative of the scale and rapidity of agricultural development in South Africa Reflecting as it does an increase in the biomass, it has tended to raise (though not necessarily proportionately) both the interception and the transpiration components of water "loss" (O_1) as well as to increase the quantity of water incorporated in the produce leaving the catchment (O_2) - and thus to decrease run-off and groundwater recharge.

Soil and water conservation and erosion control measures quickly gathered momentum after the passing of the Soil Conservation Act in 1946. The effect has been generally to retard the passage of water, thereby tending to increase the opportunity for vapour "loss" by evaporation and transpiration and so to diminish water yield.

Urban hydrology is still largely an unexplored field of study in South Africa, but impervious city streets, roofs and highways tend to promote high and rapid run-off at the expense of vapour "loss". However, as towns and cities still constitute only an infinitesimal proportion of the total area of South Africa, this accretion to the country's water yield can probably be discounted, except perhaps locally.

On the whole, reductions in water yield can be expected to outweigh gains, as is proved by the results of a statistical analysis of flow records of a number of stations in South Africa.

METHOD

To ascertain the extent to which the developing economy, as manifested in changing land use, has induced trends in run-off, it was necessary to devise a method that would discount the effects of seasonal and secular fluctuations. It was decided to test whether there has been any significant change in the run-off per unit of rainfall - irrespective of whether the rainfall was high or low - it having been established from cumulative plots of rainfall data that, despite wide annual fluctuations and some prolonged spells of wet and dry years, the annual rainfall has remained essentially constant in the long term.

The method entailed fitting a curve to the rainfall/run-off co-ordinates of each station (on a quarterly basis). It was argued that if there had been a gradual diminution in run-off per unit of rainfall, as postulated, then most of the measured run-off values of the early part of the period would tend to lie above the curve - irrespective of whether the rainfall was high or low - whereas most of the recent run-off values would fall below the curve. Gauged run-off for each year was accordingly expressed as a percentage of the corresponding long-term average derived from the curve for the rainfall in question. A trend line was fitted to these percentage values arrayed as a time series and the statistical significance of the slope of the line was determined. The method was deemed to have more power and sensitivity than covariance analysis.

The detailed procedure in analysing each station record was as follows:-

1. The total run-off in each quarter of each hydrographic year was calculated from the station record. The four quarters of the hydrographic year, which extends from 1 October to 30 September, cover the following periods -

I	:	1 October - 31 December
II	:	1 January - 31 March
III	:	1 April - 30 June
IV	:	1 July - 30 September

No adjustment was made to allow for the slight variation in length of the quarters.

2. A corresponding rainfall record was compiled by averaging the rainfall recorded in each quarter of each year at stations in and near the catchment and applying a correction factor $\frac{m}{v}$ where

m = mean annual rainfall over the catchment determined by planimetry from the 1 : 250 000 Rainfall Normal

Map, and

v = average of the long-term mean annual rainfall of the stations used.

This adjustment was necessary because the rainfall stations were not uniformly distributed over the catchment.

3. From each of the four quarterly rainfall and run-off records a curvilinear multiple regression (in natural logs) of the form

$$\ln Y_q = a + b \ln X_q + c \ln X_{q-1}$$

was derived, where

Y_q = run-off during a particular quarter of a given year

X_q = rainfall in that quarter

X_{q-1} = rainfall in the preceding quarter.

This form of expression allows for the influence on run-off of antecedent rainfall in the previous quarter. In some instances the addition of a further term X_{q-2} would have reduced the error of estimate still further but in other cases would have resulted in a poorer correlation, so that a 3-variable regression was the best compromise for general comparative use.

4. A long-term average run-off value corresponding to each value of quarterly rainfall was then derived from the expression to serve as a reference value in determining any trend (deviation) in run-off with time. In cases where the mean of this derived record differed from that of the historic record, an adjustment factor was applied.

5. Each value of quarterly run-off was then expressed as a percentage of the corresponding reference value (see 4 above).

6. These dimensionless values of run-off were then arrayed

as a time series and a linear regression was fitted, viz.-

$$P = j + kT$$

where P = percentage deviation of measured run-off from reference value, and
T = time, in years, from start of record.

It is conceded that a linear expression does not invariably yield the line of best fit. In some instances a change in run-off may be accelerating or stabilising, and periods of diminishing or increasing run-off may have alternated within the period of record. Nevertheless, an examination of the records indicated th a linear expression was not much inferior, if at all, to other fitted curves, that as a basis for estimating the rate of change it erred on the conservative side, and that it was a simple procedure that could be uniformly spplied to yield comparable results.

7. The statistical significance of the slope of the trend line (k) at the 10%, 5% and 1% levels of probability was determined by the t - test.

The criteria used in selecting stations for this analysis were that

- there should be no major upstream storage or diversion works
- the record should cover at least 15 years
- the station should be capable of measuring the full range of flow encountered - and, where this requirement was not met, the records of some quarter-years had to be discarded
- the record should be complete and continuous or vitrually so
- there should be in or near the catchment a reasonable

number of raingauges whose records covered the same period as that of the run-off record.

Preference was given to reservoir records rather than to point gauging stations. The records of 14 quarter-years had to be discarded as they were incomplete.

Table 1 shows the frequency distribution of the selected stations in relation to mean annual rainfall and season of maximum rainfall.

Table 1

	Mean Annual rainfall (mm)						Maximum Rainfall in	
	0 - 400	400 - 600	600 - 700	700 - 800	800 - 1 000	More than 1000	Summer	Winter
Number of Stations	5	3	9	11	12	10	45	5

RESULTS

Frequency of positive and negative trends

Of the 50 station records analysed 15 showed a diminution in run-off per unit of rainfall in all four quarters, while at further 12 stations the same declining trend was manifest in three out of the four quarters of the year. There was only one station at which the unit run-off increased in all four quarters and only 6 cases where there was a similar increase in three of the quarterly periods. At 8 stations the run-off per unit of run-off increased in two quarters but decreased in the others. Of the 8 station records for which only certain quarters could be analysed, the trend was negative in all quarters analysed at 4 stations and positive throughout at one station. Both positive and negative trends appear in the remaining three station records.

The rainfall/run-off relationship in the third quarter is seemingly constant where the mean annual rainfall is less than about 700 mm. With further increase in mean annual rainfall, however, the decreasing tendency becomes strongest of all the quarters.

The fourth quarter exhibits the least tendency for unit run-off to decrease in relation to increase in mean annual rainfall; again, where the mean annual rainfall is less than about 700 mm, it is more or less constant.

DISCUSSION

The analysis has confirmed the hypothesis that intensified land use associated with an actively developing economy has materially decreased the mean annual run-off over much of South Africa. Contributory factors include closer spacing, more vigorous growth and higher yields of crops (due to fertilization and hybridization), changes in land use, such as increasing afforestation, erosion control measures and the building of small farm dams which retard run-off and promote infiltration, pumping from streams for irrigation, and the like.

This feedback effect - whereby the same man-induced changes in hydrological component systems as account for increased water demands also tend generally to diminish the effective supply - is shortening the time left to meet rising water demands once they exceed the supply that can be exploite by conventional means from traditional resources. Such remedial measures are: reduction in water wastage, stabilisin water use rather than using more water per se as production increases, the conversion or diversion of water from un- productive to productive use, and harnessing additional water supplies by rainfall stimulation, desalination of seawater and the like.

An almost unexplored field of research concerns the extent to which the downward trend in run-off per unit of rainfall could be reversed by adopting land management practices that reduce vapour "losses" and so augment the water accruing to surface and ground water supplies. These might include: reduction in interception and evapotranspiration by management practices that keep pastures short except for periodic seeding, eradication of broad-leaf and deep-rooted weeds, combating bush encroachment, selection of crops that are short, shallow-rooted and have a narrow leaf rather than those which are tall, dense, deep-rooted and broad-leafed, possible use of anti-transpirants and defoliants, measures for reducing evaporation from soil, and the practice of "water harvesting" by rendering catchments partly impervious.

Run-off is one of the main criteria affecting the design and operation of a large dam. The results of this study point to the need to examine all run-off records for trends that might affect the future performance of dams and reservoirs.

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SUMMARY

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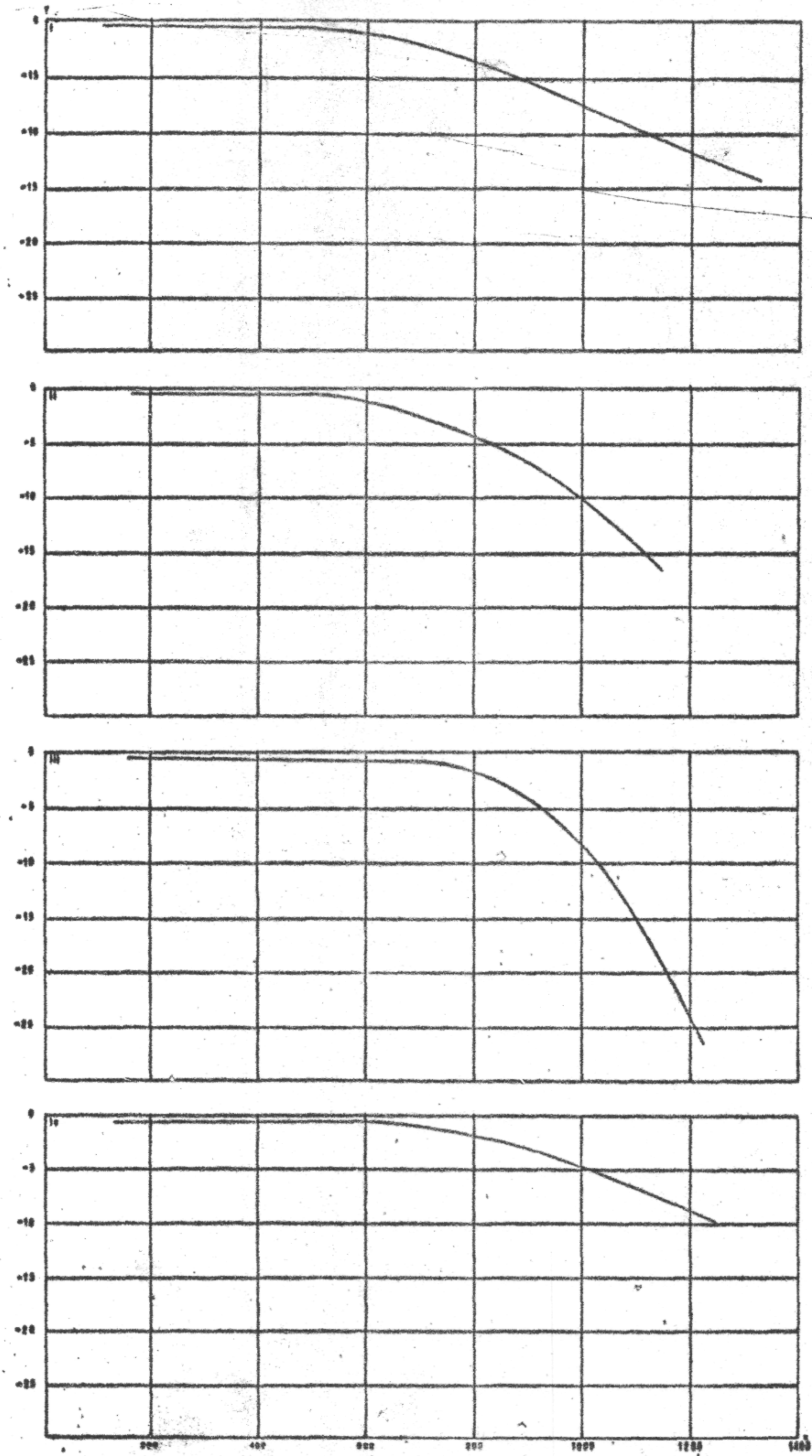

Y Average Change in Runoff [m³/ha/year] Y Changement Moyen De L'écoulement [m³/ha/année]
X Mean Annual Precipitation [mm] X Précipitation Moyenne Annvelle [mm]
I Quarter 1 I Quart 1
II Quarter 2 II Quart 2
III Quarter 3 III Quart 3