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THE HYDROLOGICAL CYCLE - PAST, PRESENT AND FUTURE.

DEUR/BY: J.S. WHITMORE.

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THE HYDROLOGICAL CYCLE - PAST, PRESENT AND FUTURE.

J.S. WHITMORE, DIVISION OF HYDROLOGICAL RESEARCH, DEPARTMENT OF WATER AFFAIRS.

As a representative of the Department of Water Affairs, I have pleasure in thanking you for your invitation to address your 11th Annual Conference. We applaud your efforts to promote the prosperity of your catchment and to safeguard its resources, notably its soil and water. Hence our pleasure at being able to participate in your Conference.

To prepare myself for this occasion I have been studying some recent statistics. Although I am well aware of the pitfalls in using statistics to propbey the future, nevertheless I venture to predict that your 16th Annual Congress will be one of special significance - for by then, according to my reckoning, there will be one million people living in, or immediately dependent on, the Umgeni catchment, if the present exponential rate of population increase is maintained. I have no doubt that such a notable occasion in your history will be fittingly celebrated. Deserving tribute will be paid to those who have laboured to develop the resources of the Umgeni catchment for the good of a million people. But Jubilee celebrations provide a fitting opportunity to look forward as well as back, and doubtless clarification of future objectives and formulation of plans to achieve those ends will feature prominently at your Jubilee Conference in a few years' time. The vital question which will require an answer then is one that has been posed here before, namely "Where do we go from here?"

Those of us who are in any way concerned with catchment resource development know what a bewildering welter of problems besets the planner. Where does he start? It is as if we stand at the fork of many roads. Some will be arduous, uphill routes, others devious twisting trails, and yet others will reach a dead-end. So compelling are the demands of an expanding aconomy that we can afford neither the time nor the cost to explore each route in turn. How then can those who have charge over natural resources select the course which will lead most surely and directly to our goal, which is, so to develop and safeguard the resources of a catchment that future expansion will be assured in perpetuity?

Surely the first need is to rationalize the problems of a catchment, to appraise them in perspective both in time and place. Moreover it is desirable to highlight local limitations and potentialities against the backdrop of broader national issues if only because, increasingly in future, development of any one region will be intimately linked with the development of the country as a whole.

That your title is the Umgeni Catchment Association, not the Umgeni River Association, is proof of your wide

interests./....

interests, and accords well with the theme of this talk which deals not with the development and use of your river but aims rather to emphasise the crucial role that management of the catchment slopes can play in governing the water potential of a valley.

To repeat: to orientate our somewhat uncertain probing along the course of future development, we need to rationalize the problems of a catchment and to view them in perspective. It is to meet this primary need that I have attempted to systematize the processes of hydrological evolution so as to provide the necessary yardstick against which both the degree of catchment development attained as well as the scope for future development, may be gauged. Although well aware that he who sets up a hypothesis sets himself up as a target for criticism, I nevertheless offer you this approach in the hope that it may prove a useful tool in anticipating future trends of development in your catchment for which timely provision must be made. The method of classification is here presented only in skeletal form, devoid of the elaboration which complete catchment analysis would demand. It refers only to surface water and assumes there is no transfer of water between catchments.

The hypothesis is compounded of three concepts.

I. Initially it recognizes four "zones of development" in a catchment - see Fig. 1.

Zone A, not always present, is the "watershed crest" of mountain peaks where the highest rainfall of the catchment generally occurs. Being more or less inaccessible this zone is generally the least subject to interference by man. In flat or undulating country where watersheds are ill-defined, this zone may be absent.

Zone B, generally by far the largest, comprising the grazed, cultivated or forested uplands from whose expanse much of the run-off from a catchment occurs.

Developmental Zone C denotes the upper reaches of the valley in which run-off collects as streamflow, where most of the storage works are built to regulate the flow of the river for use lower down.

The lower reaches of the valley, comprising Zone D, is the region where intensive irrigation, urban and industrial development is dependent almost entirely on water issuing from the upper catchment.

II. The natural characteristics of a catchment in respect of climate (essentially rainfall), topography, vegetation, soils and geology, coupled with the extent to which each catchment zone has been developed by man, determine the category or "order" of hydrological evolution of the catchment. Thus the second phase of this hypothesis reflects the degree of interdependence existing between the 4 zones of development aforementioned. At least 5 "orders of hydrological evolution" may now be distinguished (See Fig. 2):

The/.....

The First (or Primary) Order in hydrological evolution corresponds to the "natural order" which prevailed in a catchment before human settlement, or which obtains today in virgin country. It reflects the basic hydrological pattern of a catchment as established by its natural endowments.

The amount of rain falling on the catchment sets the upper limit to the volume of streamflow, while the seasonal incidence of rain, its intensity, frequency and distribution over the catchment determine the variation in flow which characterize a given river.

Of the rain that falls on a catchment a minor amount is intercepted by vegetation or detained on impermeable soil and rock surfaces, to evaporate before penetrating the soil. By far the greater part of the rainfall (an average of close on 90% for the whole of South Africa) infiltrates into the soil. Of this some percolates so far down as to augment groundwater (some of which may seep into stream channels) but most of the water entering the soil is stored there only temporarily before returning to the atmosphere through evaporation and transpiration, the rate of which is determined by local factors such as temperature, wind and atmospheric humidity.

Run-off is the residual or difference between "income", that is rainfall, and the "debits" already mentioned, namely interception, surface detention, soil retention, percolation, evaporation and transpiration. The proportion of rain which runs off the land is generally lower in a dry region than in one of higher rainfall; moreover the incremental discharge varies, the rainfall : run-off relationship approximating a semi-logarithmic exponential function in dry region than in one of higher rainfall; moreover the incremental discharge varies, the rainfall : run-off relationship approximating a semi-logarithmic exponential function in dry regions, a double logarithmic exponential function in a region of moderate, seasonally variable rainfall and a linear function in regions of fairly high, uniformly distribured rainfall.

The foregoing is essence is the familiar "hydrological cycle". At this juncture attention focusses on 4 "cardinal facts" of prime importance in the further course of hydrological evolution.

The first is that run-off is the end-product in the sequence of hydrological events, and can therefore be influenced by any of all of them.

Secondly, the magnitude of the factors involved in the hydrological cycle varies greatly. Considering the disposal of a quantity of rain falling on unit area, the amount detained on that area (through absorption by the soil and its subsequent loss through evapotranspiration or percolation) constitutes a major factor involving 75% to close on 100% of the rain falling on that area, contrasted with run-off which generally accounts for much less than 25% of the rainfall; thus even a small change in a major factor such as

infiltration/..

infiltration and evapotranspiration has an inordinately magnified effect on the smaller factor, run-off. Because of this discrepancy in order of magnitude, run-off as represented by streamflow - is extremely sensitive to slight changes in the grosser factors which precede it in the sequence of hydrological events.

Thirdly, the area contributing most of the run-off to a river - that is, Zones A and B - is infinitely large compared to the bed in which the river is confined, so any slight change in the depth of water running off the wide expanses of the catchment is greatly amplified in the flow of the river.

Fourthly, because the proportion of rain which runs off the land,is generally lowest in dry regions, a certain change in land management will have a relatively greater effect on run-off (and hereby river flow) in a dry region than in one of higher rainfall.

Still considering this natural order, topographic features now intervene to determine the character of the river evolving from run-off from the crests and uplands. The size and shape of the catchment, its geology and soil, the length and degree of slope, all combine to determine whether streamflow assembles quickly, or whether collection is longer delayed and discharge released more slowly.

Although it is now rather theoretical in concept, I have dwelt on this First Order of evolution because it is dominated by the natural features of the catchment and can therefore serve as a norm for estimating the true or inherent flow characteristics of a river such as existed before superimposition of human influences. It represents the primeval condition, a condition probably affected hardly at all by the migratory herds of game and the scattered tribes of hunters, gatherers and nomadic pastoralists who occupied the land at that time. Main cause of variations in river flow at that stage were probably flood, drought and fire.

The Second Order of hydrological evolution was induced by permanent agricultural settlement which imposed certain changes on the natural order. The Second Order represents the condition of dryland farming where the uplands and possibly also the watershed crest (Zones B and A) are worked but with no development of the river, either because low rainfall provides insufficient flow or because of a retarded economy.

While the population was sparce and there was land and to spare, farming practices included such restorative measures as shifting cultivation, the abandonment of played-out land to recuperative rest, and transhumance. Initially, therefore, effects of permanent agriculture on the hydrology of catchments was probably neither marked nor very material, there being little demand for conserved river water.

The/....

The Third Order connotes a condition where upland development is combined with construction of diversion and storage works in the upper reaches of a river (Zone C) to provide for intensive irrigation farming lower down the valley (Zone D). Now competition for water enters as a factor in hydrological evolution.

Compared with present urban and industrial water requirements, irrigation requirements are high but the demand is not increasing at the same rising tempo as the former, the limit being set by the amount of irrigable land that can be commanded by a dam and by the type of crops best suited to the area. At this order of development the main requirement is so to regulate river flow by means of storage works as to deliver a stable rather than an increasing supply of water over the years.

(Attention should be drawn to the fact that a certain proportion of river flow can never economically be stored, mainly the uncontrollable floods).

The Fourth Order of hydrological evolution relates to a catchment in which uplands are developed and again river flow is regulated by dams but to cater not for irrigation but for urban and industrial development. The demands on the river therefore differ somewhat from those in a Third Order catchment. The main problem concerns the extended provision that must be made for the steep rise in demand with time, occasioned firstly by the continuous population increase in the concentrated urban community and secondly by the rising water requirements per head of population which civilized way of life entails. To some extent this rising demand may be countered by re-use of water and its return to the river. A related problem concerns the control of river pollution by disposal of urban and industrial effluents.

The Fifth and culminating Order denotes a fully developed catchment of intensified upland management and both urban and irrigation development in the valley. The main problem now becomes the strict regimentation of the river for multiple use. In part storage may be designed for non-consumptive use - such as flood control, hydro-electric power and navigation - where the purpose essentially is to balance flow by storing surplus water to compensate for later deficiencies and where there is little actual use or loss of water other than evaporation from the reservoir. However, most of the storage will be for consumptive use and must be so planned as to deliver a more or less constant assured supply to irrigators over the years, and a rising supply to cities.

III. At this juncture the third concept of the hypothesis is introduced - that of the "margin of safety", or the span between the supply of water in a catchment (the upper boundary) and the demand (the lower boundary). Both can fluctuate and so affect the "margin of safety".

Consider/....

Consider first the supply boundary.

Assessment of the water potentialities of a valley turns upon a reliable estimate of the supply of water available for development. Such a reliable appraisal of supply is possible only in a catchment which has achieved a stable system of agriculture - what is technically known as "permanent" agriculture - on the uplands whence comes most of the run-off from the catchment. In W. Europe, for example, the present distinctive pattern of crop zones evolved centuries ago, and having become adapted to the environment and stabilised, has persisted till today. Within that pattern improvements have been effected by plant breeding, pest control, improved manurial practices and the like, but these have insignificant hydrological implications; the influence of land management on run-off is therefore very stable, and estimates of supply of water are accordingly reliable.

Few parts of South Africa, however, have attained to a system of permanent agriculture and while land use is still in the throes of trial and error, caution and good judgement are required in interpreting water resources of a catchment from river flow records - not because the river gaugings are suspect but because they may represent a transitory, unstable phase in catchment evolution. Again this emphasises the need to examine catchment problems in wide perspective.

We revert now to consideration of supply from the Second Order of evolution onwards, as competition for water increases.

It has already been pointed out that when population was still sparsely distributed, farming practices included measures which safeguarded soil stability, restored its fertility and regenerated the mantle of vegetation, thereby maintaining the hydrological equilibrium of the catchment close to the norm, or natural order. In the 1920's, however a stage was reached in South Africa when lack of new land, coupled with economic pressure, forced the abandonment of the former safe practices and marked the onset of a tendency towards explotive farming which continued unchecked for about 20 years. The more obvious consequences are well known: overgrazing, overcropping and other malpractices denuded the land of protective vegetation, caused physical, chemical and biological deterioration of the soil and drastically accelerated the natural processes of geological erosion. Less immediately apparent, though no less important, was the effect of exploitive farming on run-off: not only were variations in flow aggravated but the total percentage of run-off increased.

Since World War II there has been a swing back to conservation measures in the upper catchment. These remedial measures/....

measures are helping to restore vegetation and stem erosion but at the same time they are causing run-off, and therefore streamflow, to diminish. This is a logical phenomenon in the course of hydrological evolution if viewed in the correct perspective, and where the measures are not wasteful should not become a cause for recrimination. It means simply that run-off is tending to revert to the value associated with a stable catchment, as represented either by the Primary Order or by a system of permanent agriculture. It must be recognized from the cardinal facts mentioned earlier that the uplands, constituting as they do by far the biggest part of most catchments, will always have the prior and major claim on the water resources of a catchment.

It is an unfortunate coincidence that the two decades of exploitive farming should comprise the major period covered by many of our river flow records; as a result, there may have been a tendency to overestimate the long-term resources of some rivers, if it be conceded that run-off in those two decades was above normal being associated with retrogressive, unstable farming systems.

Attention now turns to the other component of the "margin of safety" namely, demand for water. As demand overhauls supply, or supply diminishes to the level of demand, these two boundaries of the margin of safety converge towards a point I have termed the "pivotal point" because it is the point on which all future development of the catchment turns. Once that point is reached in the process of hydrological evolution, it means that further economic growth will be halted unless means can be found to augment the water resources of the catchment. It is therefore also a focal point in revising plans and policies.

In the case of a Second Order catchment where only dryland farming is practised, the pivotal point is reached when the land is so overstocked or overcropped that stock losses and crop failures slash profits below subsistence level.

Consider next a Third Order catchment in which both dryland farming and irrigation are practised. Hitherto irrigation has been mainly confined to the drier parts of the country. Partly because rainfall is low, and run-off still more limited, and partly because irrigation in arid area requires large quantities of water utilizable river resources are generally developed to near the maximum of their assured flow, and the "margin of safety" is slender or non-existent. At present it is a catchment of this Order which is most vulnerable to even slight reductions in the volume of run-off induced by changes in land management on the catchment slopes. As an example, consider a hypothetical small catchment in a region of 20" average annual rainfall of which, say 1.5" runs off and 18.5" is retained where it falls. (See Fig. 3). Suppose that in the 1930's farmers built a series of dams, conserving in all

90%/...

90% of the average annual steamflow. If by a change in land management the amount of rain retained on the catchment were to be increased by only ½" (i.e. by less than 3%), run-off and therefore streamflow would be reduced by a third. The pivotal point would have been passed and economic degeneration caused by unwitting overdevelopment of the catchment would ensue.

In most Fourth Order catchments the pivotal point lies further in the future, but as it approaches it does so fast. (See Fig. 4.). Initial demand for water may be modest but the rate of population increase in South Africa is above the world average, to which must be added the steeply rising water requirement per head of population which industrial and urban community life engenders.

Demand in a Fifth Order catchment is a combination of that in the Third and Fourth Orders, namely, a large and stable volume of flow, progressively developed so as to accommodate steepening urban water requirements in the future.

Such then, in its simplest form, is the hypothesis of hydrological evolution that I postulate. It is now appropriate to consider where the Umgeni Catchment fits into the Scheme of things.

As statistics are rather cumbersome, I have condensed them to a simple "index of development" which has been applied to various facets of your economy against the setting of comparable conditions in the Province of Natal as a whole. The ratio of the area of the catchment to that of the Province is the reference value with which the catchment Province ratio of any other statistic is compared. Thus the population index of 5.5 implies that, for its size, or per square mile, thereare 5.5 times as many people in the Umgeni catchment as in the Province as a whole.

INDEX OF DEVELOPMENT.

Total population	5.5
White population	12.3
Non-white population	4.6
Area cultivated	2.0
Area planted to maize	1.9
Area under perennial pastures	4.3
Area under timber	3.2
European-owned cattle	1.3
Number of tractors	2.2
Number of industrial establishments	14.8
Total number of people employed in industry	15.1
Value of nett industrial output	15.3

The/....

The picture that emerges is of a densely settled catchment of most active urban and industrial growth and progressive agriculture. Clearly it is a highly developed catchment of the Fourth Order, standing on the threshold of the Fifth Order. Already its population density - close on 500 per square mile - approaches that of the most densely populated countries of West Europe and the Orient. The area of the catchment is little more than 5% that of the Province, yet today 1.6 times as many people live in this one small catchment as lived in the whole of Natal at the time of the first population census seventy years ago.

We can now speculate about the future. Certain new developments may be envisaged.

One is the possibility of an increase in irrigation in Natal - for it can be stated that in no part of South Africa where farming is practised is there always sufficient water at all seasons for intensive crop production. The world over there is a swing towards supplementary irrigation in humid areas - even in so wet a country as Holland. Humid areas are capable of far higher production than are arid areas, but the intensive methods employed to realise that high agricultural potential increase the susceptibility of the crop to effects of midseasonal dry spells. Amounts of water involved in supplementary irrigation are not great: it is the timing which is of prime importance. Nor need supplementary irrigation be confined to valley lands for spray irrigation systems can now command hillslopes. And when one recalls the intensive cultivation on steep slopes in older countries - in the Rhine Valley, in Japan, in the ancient civilizations of Peru - made possible in each case by elaborate stone terracing, then it will be surprising if similar methods are not applied within the next century to the lower catchments of Natal, enjoying as they do a mild climate throughout the year and prolific growth.

It is also logical to anticipate that the moister regions of South Africa, such as Natal, will experience a greater rate of population increase in the future as drier, less well endowed regions reach the limit of their expansion. For that contingency too, timely provision must be made.

Using even the simple hypothesis I have outlined, it is possible to gauge fairly accurately the "margin of safety" on which a catchment is now operating, and the approximate date by which that margin will shrink and converge on the "pivotal point". The time between then and now is our period of grace, in which to enforce measured to broaden the safety margin and to force apart the clamp of diminishing water supply and increasing demand, so as to provide scope for continued economic growth and to defer the pivotal point further into the future.

We must concede our lack of sufficient knowledge as to how to do this. Clearly it is a matter for further research; and because the period of grace allowed is limited, that research must be focussed on key factors which play a major and controlling role in the hydrological cycle.

There/....

There are two main avenues to be explored through research. One is the more efficient and economic use of water, both in industry and agriculture. In the latter case we are probably still far from achieving maximum crop returns per unit of rainfall - which is quite a different concept from return per acre. Thus it is known, for example, that of the considerable quantity of water that evaporates and transpires from a plant, less than 1% remains in its tissues; it is also known that there is little difference in the amount of water taken up by a stunted, starved crop and that of a vigorous, fully productive stand. Herein lies the key to efficient production in terms of crop returns per unit of water; crop variety, espacement and manurial treatment must all be tailored to the environment if the full production potential of each drop of water retained on a catchment is to be realised.

The other phase of research concerns the effect of land management on the supply of water from a catchment. There are two shortcuts to worthwhile results. The one is to concentrate research on those factors which exert by far the biggest influence on the hydrological cycle, such as transpiration and evaporation. Secondly, research should centre on those factors which can most readily be modified, that is, those which are most flexible and sensitive to management practices; a case in point is the infultration capacity of a soil which can vary by several hundred percent according to plant cover, surface compaction, drainage and the like, whereas the moisture holding capacity of a soil can be modified hardly at all.

As more and more catchments approach their pivotal point of development, a new consideration grows in prominence, one which has not merited much attention in the past. It is the need systematically to increase the water yield of a catchment. At first sight this might seem to conflict with intensification of farming and conservation practices, both of which tend to diminish run-off. Research is needed on compromise methods, such as varying the degree of conservation practised in different parts of a catchment according to their erodibility, reducing to a minimum all non-productive and non-essential storage of water in farm dams, the judicious control of riparian vegetation, and eradication of worthless vegetation. Research on water yield is only in its infancy.

Two brief examples will confirm that the effects of land management on run-off should not be underestimated. Slight changes in management of a catchment in a region of ± 10" average annual rainfall has reduced average annual flow of a South African river by 86%. Tree felling, coupled with protection against erosion, increased streamflow by 65% in a small American catchment where annual rainfall averaged 72".

The Umgeni catchment is fortunate in having within its boundaries research institutions whose work is already renowned. These organizations will be called upon to intensify their investigations still more in the future and will need all the support and encouragement you can give them.

One/....

One question remains to be answered. What will happen when the pivotal point in the evolution of this catchment can no longer be deferred? Will future economic expansion be halted? Not necessarily, for you will then seek to augment the water supplies of the catchment from without. You might explore the possibilities of "rainmaking", you might negotiate for the diversion of surplus water from another catchment, you might desalt water from the Indian Ocean or you might place a standing order with Antarctica for an iceberg to be delivered once a month to a special thawing berth at Maydon Wharf. But before resorting to measures so extreme as to verge on fantasy you would do well to sponsor dynamic research on the more immediate problems of catchment management.

I referred at the commencement of this talk to the advent of the Jubilee Conference which will mark the growth of the population of this catchment to a million people. May I suggest that you could commemorate the occasion in no more fitting and constructive manner than by amassing funds for the establish of an Umgeni Foundation, to be used for University research bursaries on the hydrological problems of your catchment.

Our good wishes accompany you on your course of progress and prosperity.

J.S. WHITMORE
HYDROLOGIST I.

13.9.61.

DIVISION OF HYDROLOGICAL RESEARCH
DEPARTMENT OF WATER AFFAIRS.

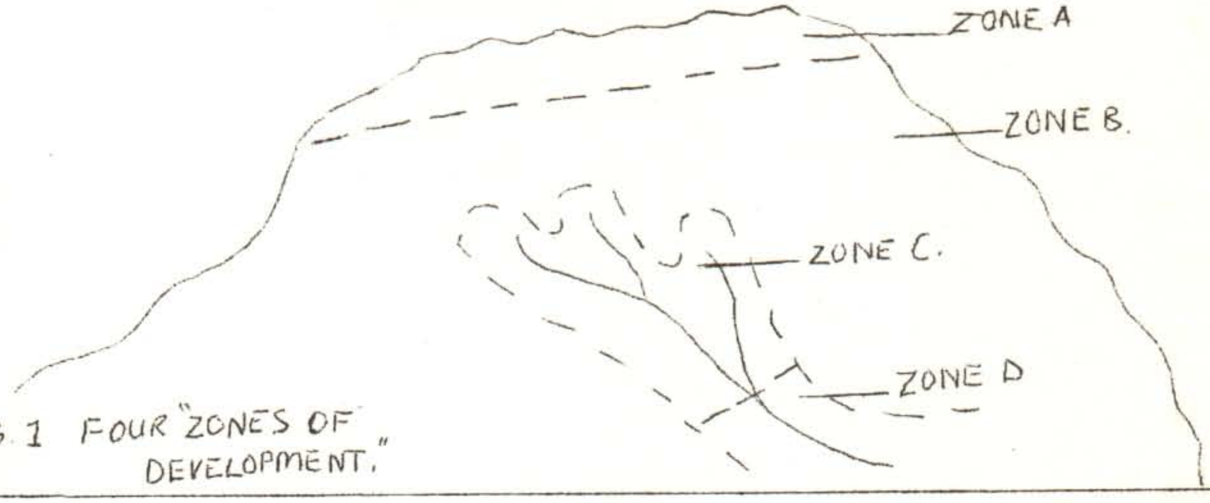

FIG 1 FOUR "ZONES OF DEVELOPMENT."

FIRST ORDER	SECOND ORDER	THIRD ORDER	FOURTH ORDER	FIFTH ORDER
Primeral Condition	Dryland Farming	Dryland Farming and irrigation	Dryland farming and urban/industrial development	Dryland farming and irrigation and urban/industrial development

FIG 2. FIVE ORDERS OF HYDROLOGICAL EVOLUTION.

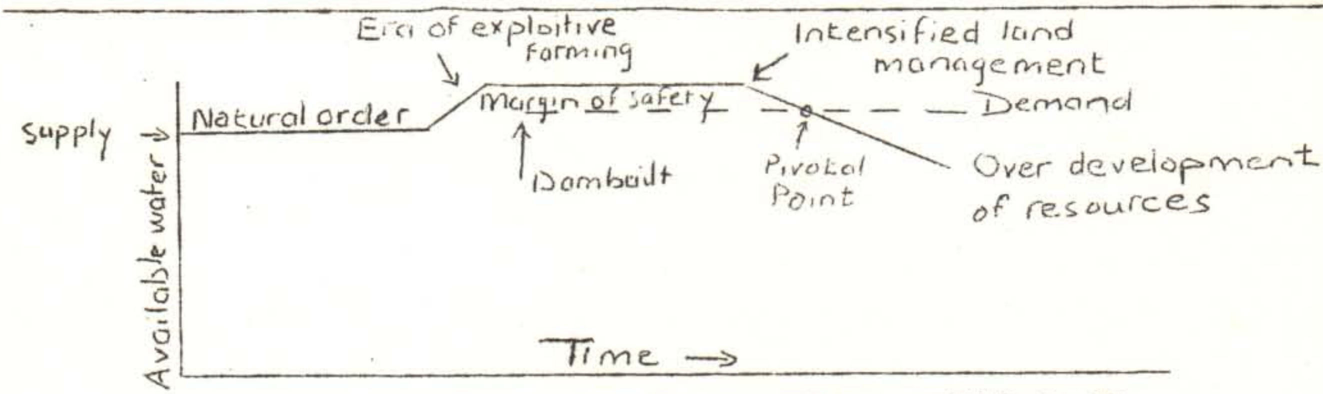

FIG 3. HYPOTHETICAL THIRD ORDER CATCHMENT,

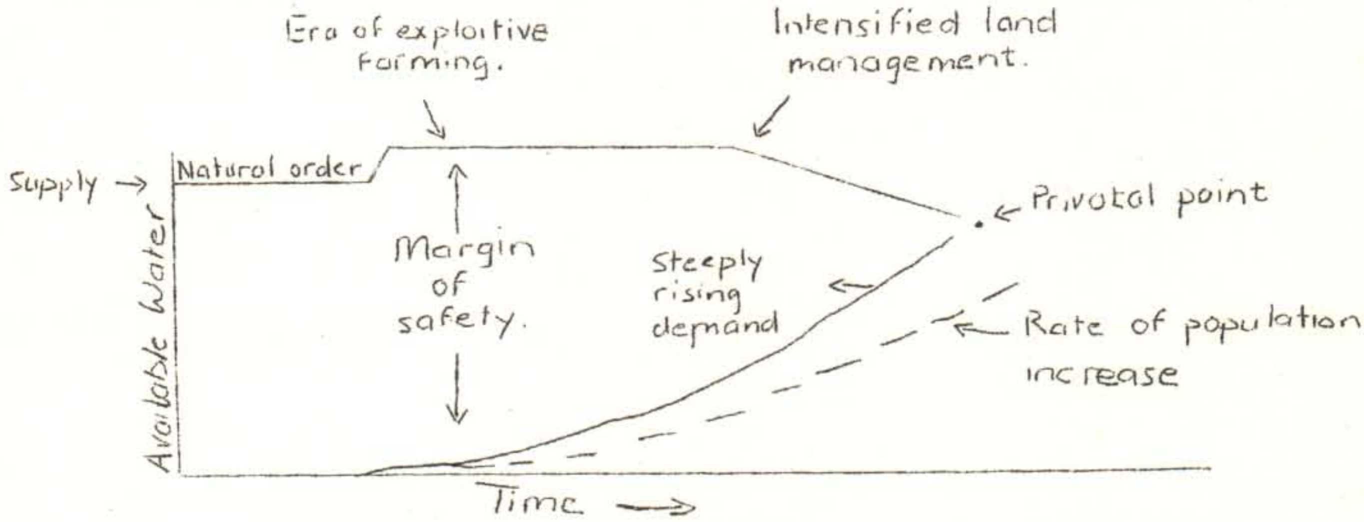

FIG. 4. HYPOTHETICAL FOURTH ORDER CATCHMENT.