The Dangers of Pollution of Limestone Aquifers, with special reference to the Mendip Hills, Somerset

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INTRODUCTION

This paper is concerned with the dangers of pollution of groundwater which may arise in aquifers composed of massive, well-jointed, limestones. In the opinion of the author, these dangers arise principally from the comparatively unusual hydrology of such aquifers. Therefore, in the discussion which follows, attention will be paid mainly to hydrological facts and arguments, rather than to the effects of particular pollutants. The bias of the argument will be towards the reasons why limestone aquifers may be particularly prone to pollution, rather than to instancing examples of such pollution occurring at the present time.

HYDROLOGICAL CONSIDERATIONS

An aquifer may be defined as a rock or group of rocks within the earth's crust from which significant quantities of groundwater are available for extraction. Most aquifers are open systems, that is, water enters them from precipitation at the ground surface, and leaves them via springs or seepages. The outflow point may be many kilometres from the recharge, or inflow, area, especially if the aquifer is artesian, or confined in a vertical direction by impermeable strata. Figure 47 illustrates the two main types of aquifer.

The value of aquifers for water supply is two-fold. Firstly, they comprise natural reservoirs which may be depleted during dry periods and recharged from rainfall or river seepage during wetter periods. Secondly, most aquifers provide a degree of natural filtration which removes solid matter from the inflowing rain or river water and ensures a supply of relatively pure water. Hence the widely held belief that one may drink with safety from springs.

This natural filtration is provided largely by aquifers which are composed of fine or medium grained rocks, such as mudstones or sandstones, or fine grained alluvial deposits. The groundwater fills and moves through the interstices between the grains, and these are small enough to filter out most solid matter. In addition, the flow is usually laminar, so that solid matter settles out. Bacteria and other organisms in the water tend to adhere to the solids and are thus also removed. This is the same principle as that on which filter beds operate. In fact, the smaller the grain size of the rock, the smaller are the pore sizes, and the more effective the filtration. Thus, unconsolidated deposits such as alluvium, which are often fine enough grained to form effective filters, but have sufficient numbers and sizes of pores to ensure a high permeability and easy transmission of water, form good aquifers.

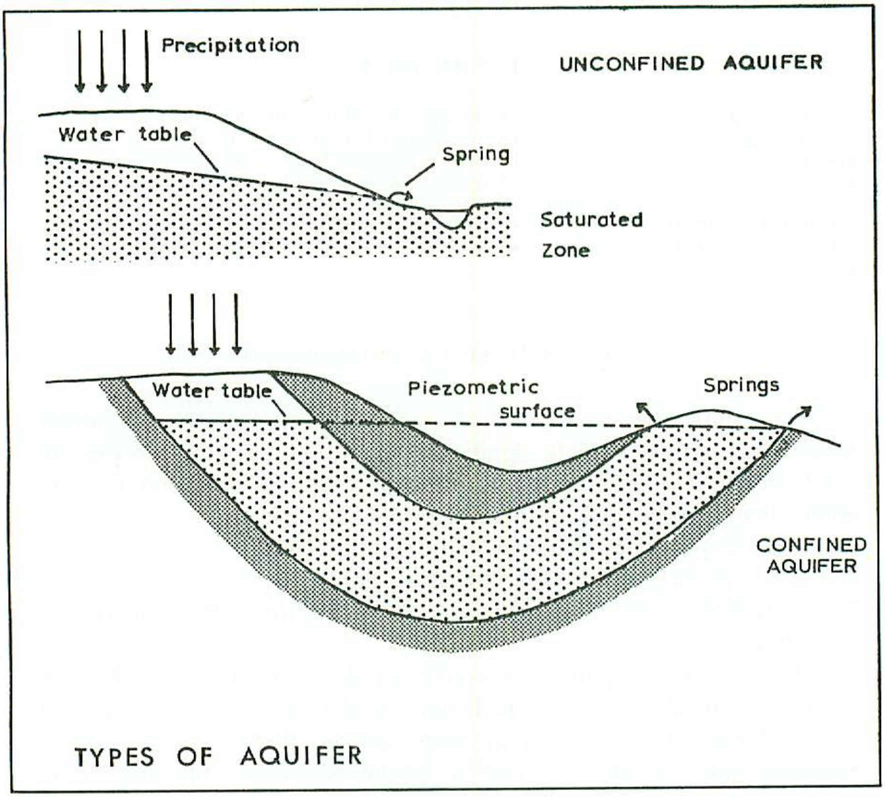

Fig. 47

However, most important aquifers, apart from unconsolidated deposits, have a high proportion of porosity made up of secondary voids—cracks, joints, bedding planes, and other fissures. Compared with the permeability along secondary voids, the primary permeability is often very low. For example, the values of permeability of chalk determined in the laboratory (mainly primary permeability) vary between $1 \cdot 5 \times 10^{-1}$

and 3·7 litres per day per metre lpd/m, while the permeability determined in the field (primary *plus* secondary permeability) is between $1{\cdot}5 \times 10^3$ and $1{\cdot}5 \times 10^4$ lpd/m, which is about four magnitudes greater (Ineson, 1961). If, however, the secondary voids are narrow and form a close mesh so that flow in them is laminar, natural filtration and sedimentation still occur in the groundwater body. Table 1 shows primary porosities and field permeabilities of some British aquifers.

TABLE 1: POROSITIES AND PERMEABILITIES OF SOME AQUIFER MATERIALS

POROSITIES

Material	*Primary Porosity*	*Source*
Carboniferous Limestone	0.18%	Drew, 1968
Old Red Sandstone	6.6%	Drew, 1968
Inferior Colite	10.4%	Drew, 1968
Great Colite	c.0.8%	Goudie *et al.*, 1970
Chalk Rock	c.3.5%	Goudie *et al.*, 1970
Chalk	c.11 %	Goudie *et al.*, 1970

PERMEABILITIES

Material	*Primary Permeability*	*Primary plus Secondary Permeability*	*Source*
Chalk	1.5×10^{-1}—3.7 lpd/m	1.5×10^3—$1{,}5 \times 10^4$ lpd/m	Ineson, 1962
Alluvial deposits	3.0×10^3 lpd/m	—	Ineson and Downing, 1965
Alluvial deposits	1.5×10^3—1.5×10^4 lpd/m	—	Ineson and Downing, 1965

The chemical composition of groundwaters is found to change as they pass through rocks of different composition, or are supplemented by percolation water of different composition from themselves. Thus, some solutes may be precipitated, or some toxic substances rendered harmless by reaction with the rocks of the aquifer.

The case of massive, well-jointed, limestones with a low primary porosity is rather different. Such rock types are represented best in Britain by the Carboniferous Limestone, and elsewhere by other parts of the stratigraphic column. The Carboniferous Limestone has a primary porosity of 0·18 per cent. in the eastern Mendip Hills, Somerset. In this area, its primary permeability is negligible. However, the limestone normally has a pronounced secondary porosity and permeability, especially when it is present in a topographically elevated position. In this situation, the Carboniferous Limestone tends to erode to form karst scenery, one of the characteristics of which is caves. These, of course, vastly increase the local permeability. During the past decade, extensive studies have been made of the processes of erosion and hydrology on the Carboniferous Limestone of the Mendip Hills, Somerset, by a group of workers at the University of Bristol, led by D. Ingle Smith. The results of this work, as they affect the dangers of water pollution, are discussed below. While they are drawn from a single area, they apply in principle to any upland area composed of massive, well-jointed, limestones.

The Mendip Hills are an upland area of Carboniferous Limestone and Devonian Old Red Sandstone rocks, stretching from approximately Weston-super-Mare in the west to Frome in the east. The sandstones, which are impermeable in the west and contain usable groundwater in the east, form the highest parts of the hills. They outcrop in the cores of asymmetric periclinal folds, forming east-west whale backed hills. These stand above the level of the Carboniferous Limestone rocks, which underlie an undulating plateau at 230–260 m.O.D. The limestones dip away from the sandstone outcrops at angles varying from a few degrees to the vertical. Plate 23 illustrates the outcrop of the Carboniferous Limestone.

Streams collect water on the sandstone areas and on reaching the edge of the limestone invariably sink into sinkholes or swallets, beneath which are caves. A number of the latter have been explored, some to depths of 150 m. or more. The cave passages are of relatively large size, in normal groundwater terms, varying from a few centimetres high to tens of metres high and wide. The streams in them are turbulent, not laminar, and are found in passages with an air fill as well as those with a complete water fill. Many of the Mendip streams have been traced, using dyes or lycopodium spores, to springs around the foot of the steep slopes which flank the plateau to the north and south (pl. 23). All of the water draining from the plateau can be assumed to emerge at these springs, from several of which Bristol Waterworks Company extracts a total of 159 million litres (35 million gallons) per day for use in drinking water and other supplies.

The water recharging the Carboniferous Limestone aquifer may be divided into three types. The first of these is *swallet water,* which comprises all of that water entering the aquifer as discrete streams, through discrete swallets. The other two types may be grouped together as *percolation water* which is simply that water which enters the limestone or the soil directly it reaches the ground as precipitation, and percolates more or less vertically downwards. Percolation water may be divided into *vadose trickles* and *vadose seepage.* (These two latter terms do not appear elsewhere in the literature, but are adopted here for convenience). *Vadose trickles* are trickles and streams which collect their water from the soil and sub-soil, become quickly integrated into small streams on entering the limestone, and thereafter flow quickly to points where they enter caves, or join other *vadose trickles.* Their channels are essentially similar to miniature cave passages, but are often too small to enter. They are frequently seen as tributaries to cave streams, most of which belong to this class of percolation water. Heavy drips and showers from cave roofs are also often *vadose trickles.* These fluctuate rapidly in discharge in response to precipitation and soil moisture changes on the surface.

Vadose seepage is slow-moving water, occupying tight joints and fissures in the rock. They are seen chiefly as slow-forming drips on the roofs of caves. Their discharge fluctuates much less than that of *vadose trickles*, and they show a very much slower response to rainfall. To judge from the various tributaries and drips in the major Mendip caves, *vadose seepage* is quantitatively insignificant when compared with *vadose trickles*.

Water budgeting studies carried out by Tratman (1963), Drew (1967a, 1968), Newson (1970), and unpublished work by the present writer show that percolation water comprises between 90 and 100 per cent. of low flows at springs. Only 0–10 per cent. at low flows, and up to 35 per cent. at high flows, is swallet water. In exceptional flood conditions, swallet water may comprise 50 per cent. of the flow for a brief period. As stated above, *vadose trickles*, which flow in relatively open channels and pipes, comprise the great majority of this percolation water. Thus, neither the swallet water, nor most of the percolation water, receive any filtration from the aquifer. This is because the latter is much more similar to a system of town drains, or in the flooded parts to a mains water supply network, than to the close mesh of small cavities found in aquifers such as the Oolites of the Cotswolds, or the Chalk.

This lack of filtration is borne out by the fact that at high flows all of the major springs show signs of turbidity. In very high flows, such as those of 10–11 July 1968, sediment concentrations of over 2,000 parts per million (ppm) have been recorded, while in more frequently occurring floods, concentrations of tens or hundreds of ppm may occur (Newson, 1970; Hanwell and Newson, 1970).

While the storage capacity and reservoir volume of the Mendip aquifer are as yet unknown, water tracing by tagging water with dyes or lycopodium spores has shown that travel times are very swift. Both swallet and percolation waters have been traced, travel times being between three hours and six or seven days from swallet to spring at periods of low flows, and rather less at high flows. The travel time at any given moment for any point will depend upon stream discharge, soil moisture, precipitation, distance of the point from the outflow, and the local geology. However, the mean first arrival time for twenty-seven traces of swallet and percolation water was twenty-seven hours. In other experiments, dyes were placed on or in the soil, up to 800 m. distant from springs. They reappeared within ten days of rainfall in all cases (Drew, 1968; Drew, Newson, and Smith, 1968). Similar evidence of the rapid transmission of water through the aquifer is given by the response of springs to rainfall. This shows a varying lag, depending upon the magnitude of the rainfall, its intensity, and the antecedent soil and groundwater conditions. The lag generally lies between six and twenty-four hours for the start of response, with somewhat longer lags from the moment of peak rainfall intensity to that of peak discharge. The aquifer may take up to two weeks to drain after floods.

It is clear from the preceding paragraphs that any pollutant introduced into the groundwater circulation in the limestone aquifer can be expected to reappear at a spring within a few days in periods of normal flow. It will have received virtually no filtration.

Figure 4 summarises the general nature of drainage within the Carboniferous Limestone aquifer. It will be noted that the soil is a prominent feature of the diagram. The Mendip area is an agricultural one, and much of the land is used for the grazing of cattle and sheep. Similarly, fertilisers and selective weedkillers are applied to the ground, and the manufacture of silage, and the husbandry of pigs in piggeries both produce noxious effluent. Where these various potential pollutants are separated from the limestone bedrock by the soil, which in this area is up to 1 m. thick, no unacceptable pollution of groundwater normally occurs. This is because the soil forms a natural filtration barrier. In cases where such substances as those mentioned above are allowed to leak into the aquifer in

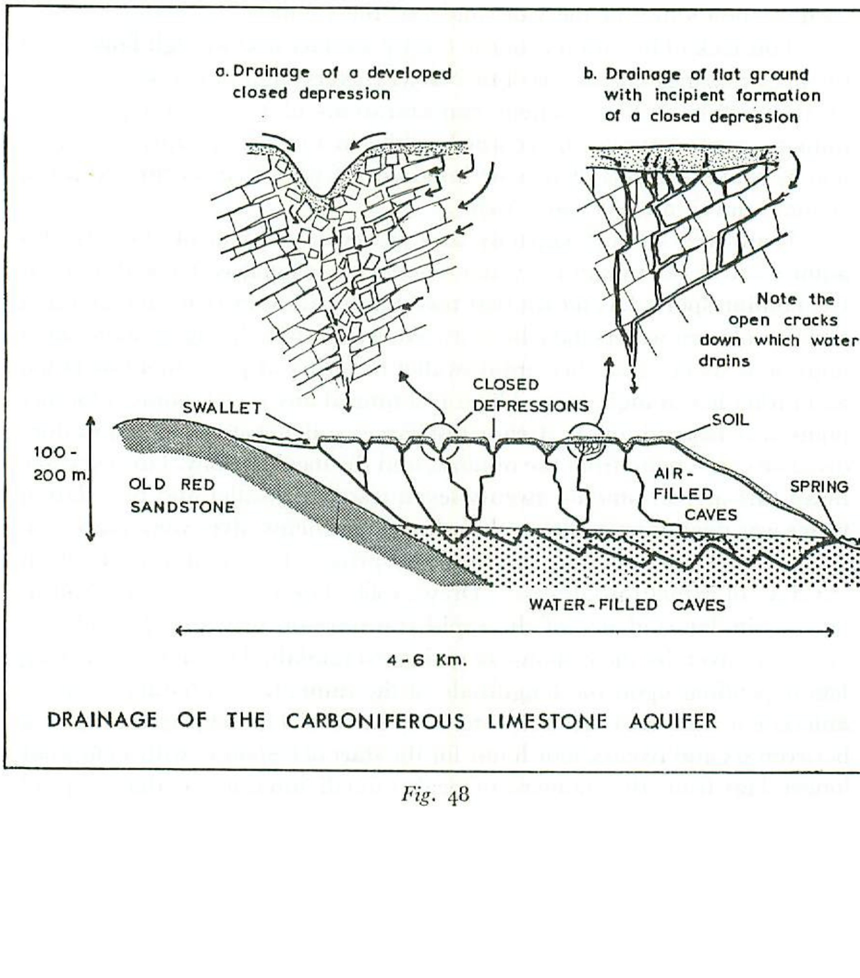

Fig. 48

large quantities, the effect at springs and sources of water supply will be swift and obvious. This fact is of paramount importance, and cannot be stressed too much. Thus, the practice of dumping rubbish, or, worse, industrial and commercial wastes into closed depressions and holes in the ground on the Mendips is an extremely dangerous one, and could very easily lead to serious pollution of water supplies.

It should not be thought from the paragraph above, that the presence of a soil cover renders the aquifer immune from pollution. *The soil has only a limited capacity for filtering and buffering potential pollutants*, and this capacity itself varies from place to place. Obviously, it is less where the soil is thinner, and although the thicker soils of the Nordrach Series (Findlay, 1965) are up to 1 m. thick, large areas, especially in the central and western Mendips, are covered with the thin Lulsgate Series and Mendip Complex soils, which may be as thin as a few centimetres. Closed depressions, which have in the past been used for the illegal dumping of oil wastes (Information from Bristol Avon River Authority) are often completely soil covered. Excavation of a number of these depressions by caving clubs has shown, however, that the soil in them often contains drainage pipes and channels. Observations at several sites has shown also that these depressions form a focus for local drainage from the soil, and may take quite large streams (*vadose trickles*) in wet weather (Ford, 1963; Ford and Stanton, 1968).

Since the Mendip Hills are an important source of water supplies, it is important to know what springs are likely to be affected should a serious incident of pollution due to, say, dumping occur at a particular point. Plate 23 shows all of the underground connections that have so far been established by water tracing, and in addition, a rough delineation of the catchment areas of the major springs. The latter should be regarded as approximate. However, a catchment boundary has been shown only when there is at least some evidence about it from water tracing. In cases where no direct evidence has been discovered, no boundary is shown. The only exception to this is the boundary between the Wookey Hole/Rodney Stoke catchment and the Cheddar catchment, which is shown by a dotted line, and which is presumed to lie somewhere in the area of that line.

DISCUSSION AND CONCLUSIONS

The case of the Carboniferous Limestone aquifer in the Mendip Hills has been discussed, and it has been shown that the nature of the water flow in the aquifer is such that water receives no natural filtration once it has entered the limestone, but that in the majority of cases the soil forms a limited but effective filtration barrier for most types of agricultural pollutants. Thus, farm drainage, fæcal wastes from animals, sheep dips, selective weedkillers, and nitrogenous fertilisers do not normally present a pollution hazard. A much greater hazard is introduced when pollutants are introduced directly into the limestone, beneath the soil, in which case no natural filtration occurs between the site of introduction and the springs. Such hazards occur constantly from poorly maintained domestic septic tanks and soakaways, especially if these do not have filter beds; from discharge of quarry waste, farm drains, and sewage into streams; and from the dumping of refuse or industrial or commercial wastes into closed depressions or quarries. Appendix 1 lists a number of sites at which such hazards are extant at present, or have been so in the recent past. It is by no means a complete list.

While this discussion has been limited to the area of the Mendip Hills, there is no reason to believe that the hydrological arguments and facts involved will not apply to a greater or lesser degree to any upland area of massive limestone. Examples of such areas are to be found in the Carboniferous Limestone outcrops of western Ireland, north-west Yorkshire, the southern Pennines, Devon, and south and north Wales. The degree of hazard will in practice depend upon the soil types, land use, population, and local industries of the area in question. However, it should always be borne in mind that the hydrology of this type of limestone terrain is such that the filtration of groundwaters is minimal, and the danger of pollution of groundwaters is thus higher than in other areas, with a more normal groundwater circulation.

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APPENDIX 1
RECENT AND CONTINUING EXAMPLES OF WATER POLLUTION ON THE MENDIP HILLS

1. *Swildons Hole:* Farmyard drainage from Priddy Green (NGR 527510) arrives in cave stream from ascending shafts in the roof (Cowsh Avens). Spring affected: Wookey Hole.
2. *Lower Farm, Charterhouse:* Farmyard drainage was discharged into the Longwood stream; this has now ceased. At *Longwood Swallet* (NGR 486557) a septic tank discharges into the ground. The effluent can be seen in the cave 15 m. below. Spring affected: Cheddar.
3. *Manor Farm, Charterhouse:* Farmyard and road drainage discharge into a swallet. A septic tank further down valley leaks into a cave 20 m. below. (NGR 498557ï) Spring affected: Cheddar.
4. *Eastwater Farm, Priddy:* Farmyard drainage and septic tank overflow discharge into a closed depression. The effluent is detected in a cave 30 m. below. (NGR 537509.) Spring affected: Wookey Hole.
5. *Stoke Lane Slocker:* Pollution of the slocker stream by rock dust and phenolic and cresolic tars from local quarries. Position, 1970, greatly improved. (NGR 669474.) Spring affected: St. Dunstans Well.

6. *Haydon Farm Swallet:* Farm drainage and untreated sewage discharged into swallet. (NGR 585483.) Spring affected: St. Andrews Well.
7. *Biddlecombe Stream:* Polluted by organics, mainly farmyard or other faecal drainage. Source of pollution not known. (NGR 568471.) Spring affected: St. Andrews Well.
8. *Nedge Hill Sink:* In 1967 a Bristol cleansing firm dumped 50,000 galls of oil and cyanide into this small cave. The firm was successfully prosecuted. (NGR 586515.) Spring affected: Unknown.
9. *Devil's Punchbowl:* In 1967 the same firm dumped 20,000 galls of oil in this depression. Traces of oil were smelt and detected at Compton Martin. (NGR 543538.)
10. *Priddy:* In 1969 and 1970 the same firm was observed tipping wastes into an abandoned quarry at NGR 555500.
11. *Fairy Cave Quarry:* The quarry contains several caves. A small stream in Hilliers cave was polluted by tar percolating from the quarry floor, and the same cave is now closed by several thousand tons of rock sludge. (NGR 657477.)

This list gives examples only and is not exhaustive. All grid references refer to ST (31).

KEY TO PLATE 23
SWALLETS AND CAVES

1. Reads Cavern
2. Bath Swallet
3. West Twin Brook
4. East Twin Brook
5. Ellick Farm Swallet
6. Ubley Hill Pot
7. Tynings Farm Swallet
8. Longwood Swallet
9. Manor Farm Swallet
10. Blackmoor Swallet
11. Pine Tree Pot
12. Vee Swallet
13. West End Mine Shaft
14· Brimble Pit
15. Waldegrave Swallet
16. Swildons Hole
17. Eastwater Cavern
18. Plantation Swallet
19. Hillgrove Swallet
20. Easter Hole
21. Whitsun Hole
22. Zoo Swallet
23. Rock Swallet
24. Biddlecombe Swallet
25. Haydon Farm Swallet
26. Golf Course Swallet
27. Emborough Swallet
28. Binegar Bottom Slocker
29. Little London Slocker
30. P 3
31. P 2
32. P 1
33. Stout Slocker
34. Oakhill Slocker
35. Springfield Slocker
36. Blake's Farm Slocker
37. Larkshall Slocker
38. Midway Slocker
39. Withybrook Slocker
40. Brickdales Inn Slocker
41. Stoke Lane Slocker
43. East End Slocker
43. Pitten Street Slocker

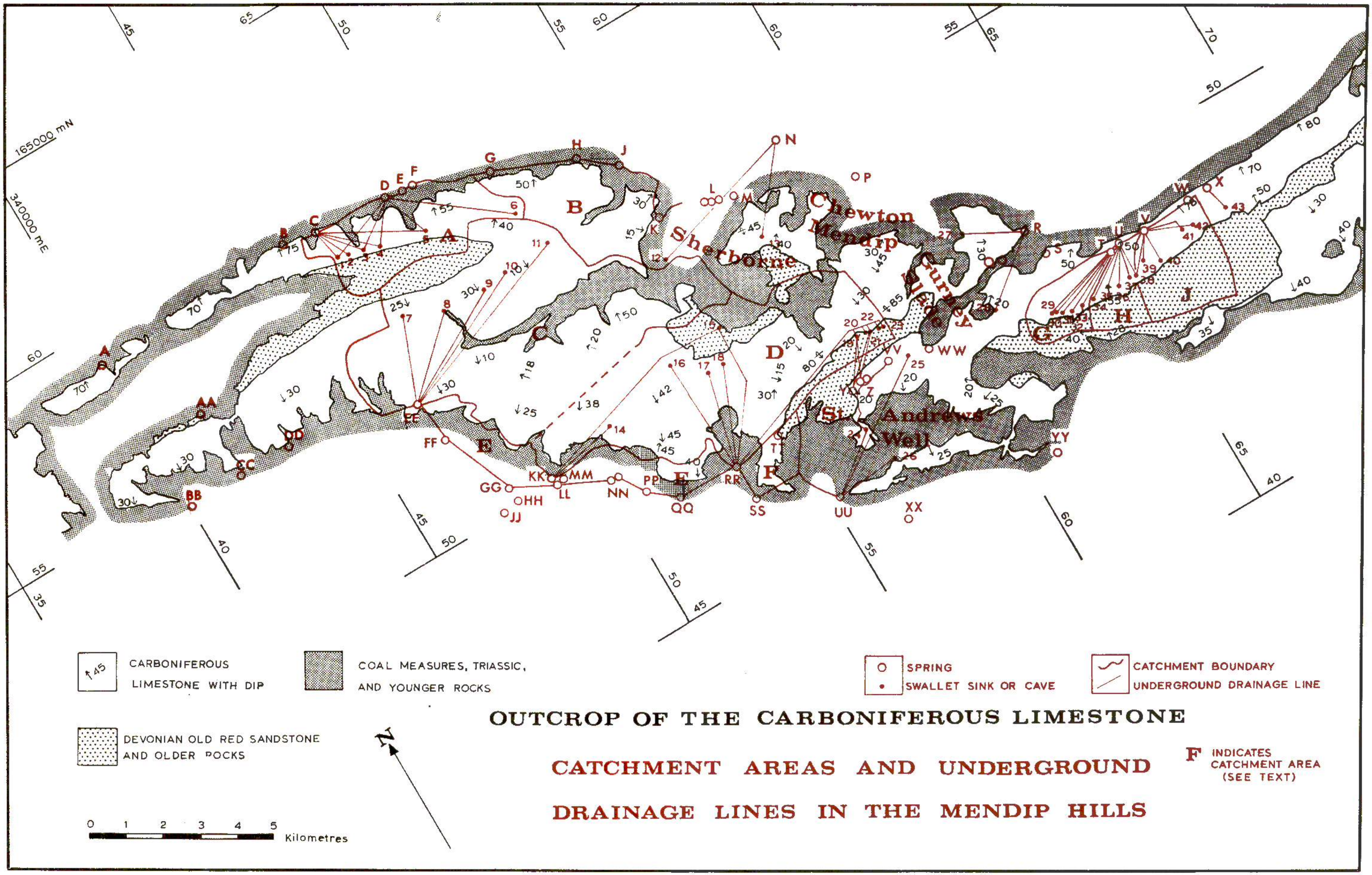
CATCHMENT AREAS

A. Burrington Springs
B. North Flank Springs
C. Cheddar
D. Wookey Hole/Rodney Stoke
E. South Flank Springs
F. Glencot
G. Ashwick Upper Springs
H. Ashwick Lower Springs
J. St. Dunstans Well

SPRINGS

A. Banwell
B. Saye's Lane
C. Langford
D. Rickford
E. Squire's Well
G. Combe Lodge
F. Rookery Farm
H. Barrow Well
J.J. Compton Martin
K. Garrowpipe
L. Pitt Farm
M. Buckley Wood
N. Sherborne
P. Chewton Mendip
Q. Winter Well
R. Gurney Slade
S. Blackey Well
T. Ashwick Upper
U. Ashwick Lower
V. St. Dunstan's Well
W. Bector Wood
X. Whitehole
Y. Biddlecombe West
Z. Biddlecombe East
Central and Lower East

AA. East Well
BB. Dunnett
CC. Cross
DD. Axbridge
EE. Cheddar
FF. Halfway (Laubram)
GG. Barnet's Well
HH. Honeyhurst
JJ. Rowpits
KK. Rodney Stoke (Wellhead)
LL. Spencer's Spring
MM. Scaddens Lane
NN. Westbury
PP. Hollybrook
QQ. Easton
RR. Wookey Hole
SS. Glencot
TT. Rookham and Vigo Wood
UU. St. Andrew's Well
VV. Biddlecombe Upper East
WW. Slab House
XX. Dulcote
YY. Darshill



CARBONIFEROUS LIMESTONE WITH DIP
COAL MEASURES, TRIASSIC, AND YOUNGER ROCKS
DEVONIAN OLD RED SANDSTONE AND OLDER ROCKS
SPRING
SWALLET SINK OR CAVE
CATCHMENT BOUNDARY
UNDERGROUND DRAINAGE LINE
OUTCROP OF THE CARBONIFEROUS LIMESTONE
CATCHMENT AREAS AND UNDERGROUND DRAINAGE LINES IN THE MENDIP HILLS
F INDICATES CATCHMENT AREA (SEE TEXT)
0 1 2 3 4 5 Kilometres
N
165000 mN
340000 mE
Sherborne
Chewton Mendip
Gurney Slade
St. Andrews Well

PLATE 23