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Hydrological and Ecological Problems of Karst Regions

Hydrological actions on limestone regions cause distinctive ecological problems.

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The ecological patterns of the land regions of the world are classified in many different ways. They are seldom classified according to their relationships to the underlying rocks because generally the ecological zones or belts are so extensive that they encompass a wide variety of rocks. Moreover, in most regions the influence of climate is so great that it tends to mask the more subtle influence of the underlying rocks except for some special situations. Limestone terranes form one distinctive exception. It is my purpose in this article to point out the relationships of hydrology to the ecology in limestone regions that have been altered by processes of karstification. The results of karstification, such as scarce soils and water at the land surface, so obviously control the existence and behavior of organisms that a gross understanding of the ecology can be assumed and need not be explicit for this purpose.

The term "karst" has long been used to define the sum of the phenomena characterizing regions where carbonate rocks, chiefly limestone, are exposed. "Karstification" refers to the many processes that result in the development of surface and subsurface features that are distinctive in many carbonate rock terranes. Karst features develop where water containing carbon dioxide has been able to move on and through carbonate rocks and to remove some of the rock in solution.

The development of karst features, particularly caverns and other large openings, depends on (i) the presence of soluble rocks, (ii) the presence of carbonic acid, (iii) ample precipitation, (iv) openings in the rocks, and (v) a favorable topographical and structural setting.

The ecology of carbonate rock regions ranges greatly, depending on climate, of course, but also on several gross geologic factors. There are delicate balances in the development of karst areas that are related to the character of the rock: whether it is essentially pure, whether it contains insoluble material throughout or only in thin discrete beds, and whether it has primary permeability or secondary permeability through fractures and caverns. Geologic structure and history are everywhere involved in karst development because carbonate rocks must be uplifted from below sea level to the landscape environment where fresh water can infiltrate and move through them. Such structural conditions as folding and faulting may cause the rock to lie below or within the local water circulation system. Topographic relief gives impetus to circulation of water. Only within the freshwater system can the full interplay of climate, topography, and geology exist to develop karst features.

The interplay between carbonate rocks and climatic, geologic, topographic, and hydrologic factors creates a wide variety of environments, ranging from the subsurface to the surface and particularly determining soil patterns and water distribution. These environments, in turn, have had their effect on the local development of plants and animals and on the culture and history of man. Many problems of carbonate terranes are related directly to the influence of carbonate rocks on the local hydrologic regimen. By defining the problems and putting them into perspective it may be possible to improve man's understanding of the economic and ecologic balances in regions where carbonate rocks occur.

Some of the characteristic problems of carbonate rock terranes, such as those related to scarcity of soils, scarcity of surface streams, and rugged topography, are obvious and somewhat distinctive; these characteristic features are developed by natural processes. In fact, natural processes in some carbonate regions may have caused a greater restriction in the development of biota than man can ever be suspected of causing. There are complex insidious problems that develop as man disturbs the natural balance of geologic and hydrologic conditions in carbonate rock terranes. It is necessary to understand environmental relationships—especially those involving hydrology—to determine whether actions by man affecting one part of the carbonate rock system will have a direct or indirect detrimental effect somewhere else in the total carbonate rock system. It is conventionally considered that man inherits a good natural environment but that he tends to degrade it. A contrary consideration may be posed in the following questions. Has man inherited a rather harsh and poor environment in carbonate rock terranes? If so, can he improve it?

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Ecological Problems

The ecology of any region is inherently related to climate, topography, soils, and of course, to the complex of characteristic biota. An additional factor that may be called "terrane permeability" is especially significant to the ecology of carbonate rock terranes. Features of climate, topography, and soils are observable or discernible and, therefore, do not need amplification for this discussion. Permeability, on the other hand, is less readily discernible and has a bearing on many human problems in karst terranes.

Carbonate rocks are exposed and karstified in glacial, temperate, and tropical settings that range from wet to very dry. Karst in arid regions, such as that in the Western Desert of Egypt and in the Nullarbor Plain of Australia, is mostly a relic of development during an earlier and more humid period.

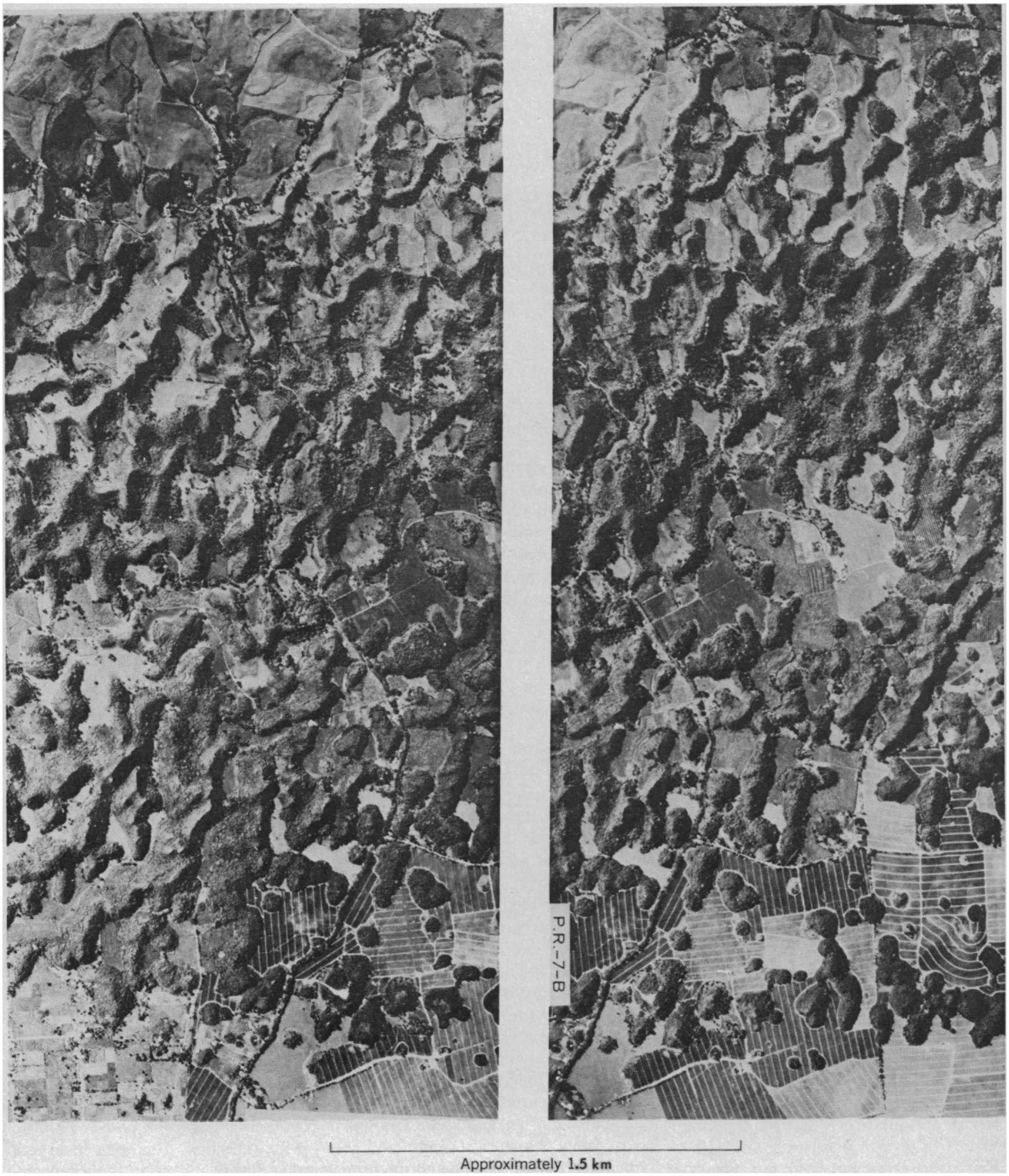

Fig. 1. Stereoscopic view of a karst terrane in northern Puerto Rico (U.S. Geological Survey, Manatí quadrangle, 7.5′). The rugged topography consists of sinkholes and towers.

Karst topography is uneven. The unevenness ranges from subdued topographic relief in some sinkhole areas to precipitous sinks and conical hills, typical of the Cockpit Country of Jamaica, West Indies, and parts of northern Puerto Rico (Fig. 1). Differential erosion is common where soluble carbonate rocks are adjacent to nonsoluble rocks and, depending on imbalances of several factors, the carbonate rocks stand either higher or lower than the adjacent rocks. In the warm humid Appalachian region of the eastern United States the carbonate rocks tend to occupy elongated valleys, but in many other regions, such as in the arid Southwest, the carbonate rocks make prominent ridges. In some areas, the terrane is so rugged that human habitation and communication are limited, as in parts of Yugoslavia and Greece.

While undergoing karstification, many carbonate rocks leave little insoluble residue, and their soils are regenerated more slowly than those on nonsoluble rocks. Once carbonate rocks on upland slopes have been stripped of soil, they tend to remain denuded, even in humid regions where soil-forming processes are favorable. Soils of upland karst regions are washed into sinkholes and other karst lowlands. In some low-lying areas, the soils are protected from further removal long enough to form laterite and even bauxite.

The permeability of the entire carbonate rock system is important because while caverns and other openings are enlarging and while permeability is increasing, the water table is progressively lowering itself to greater depths below the land surface. Permeability does not at first glance seem significantly related to ecology, but many practical problems in carbonate areas are related to permeability. These include (i) scarcity and poor predictability of groundwater supplies, (ii) scarcity of surface streams, (iii) instability of the cavernous ground, (iv) leakage of surface reservoirs, and (v) an unreliable waste-disposal environment.

1) *Scarcity and poor predictability of groundwater supplies.* Although the extremely high permeability of some carbonate rocks results in high yields of wells, in other areas the high permeability causes the water to drain quickly out of the region or to great depths. In Bermuda, for example, the permeability of the near-surface limestone is so great that water quickly moves into the ground and laterally to the sea, and only a thin sheet of fresh water lies on the basal salt water. The Miami area of Florida has a comparably high permeability, but the quartz sand in the solution openings reduces the permeability slightly and slows down the outflow to the sea. The limestone in Bermuda can hardly be called an aquifer, whereas that in Miami is one of the most prolific water producers known. In most karst regions of the world the permeability is too high or too low for water supply needs.

The uneven distribution of permeability in most karst aquifers leads to several types of problems. The preferential circulation of water along some fractures and the enlargement of these fractures by solution causes an arterial system in which water tends to collect in large openings and to discharge as widely spaced large springs. Wells penetrating the large openings have yields much greater than those that end in rock with smaller openings. The yield of wells in such an arterial system cannot be predicted consistently because the common techniques of interpolation and extrapolation, so useful in more homogeneous aquifers having more uniform flow, are not applicable in simple form. The permeability tends to

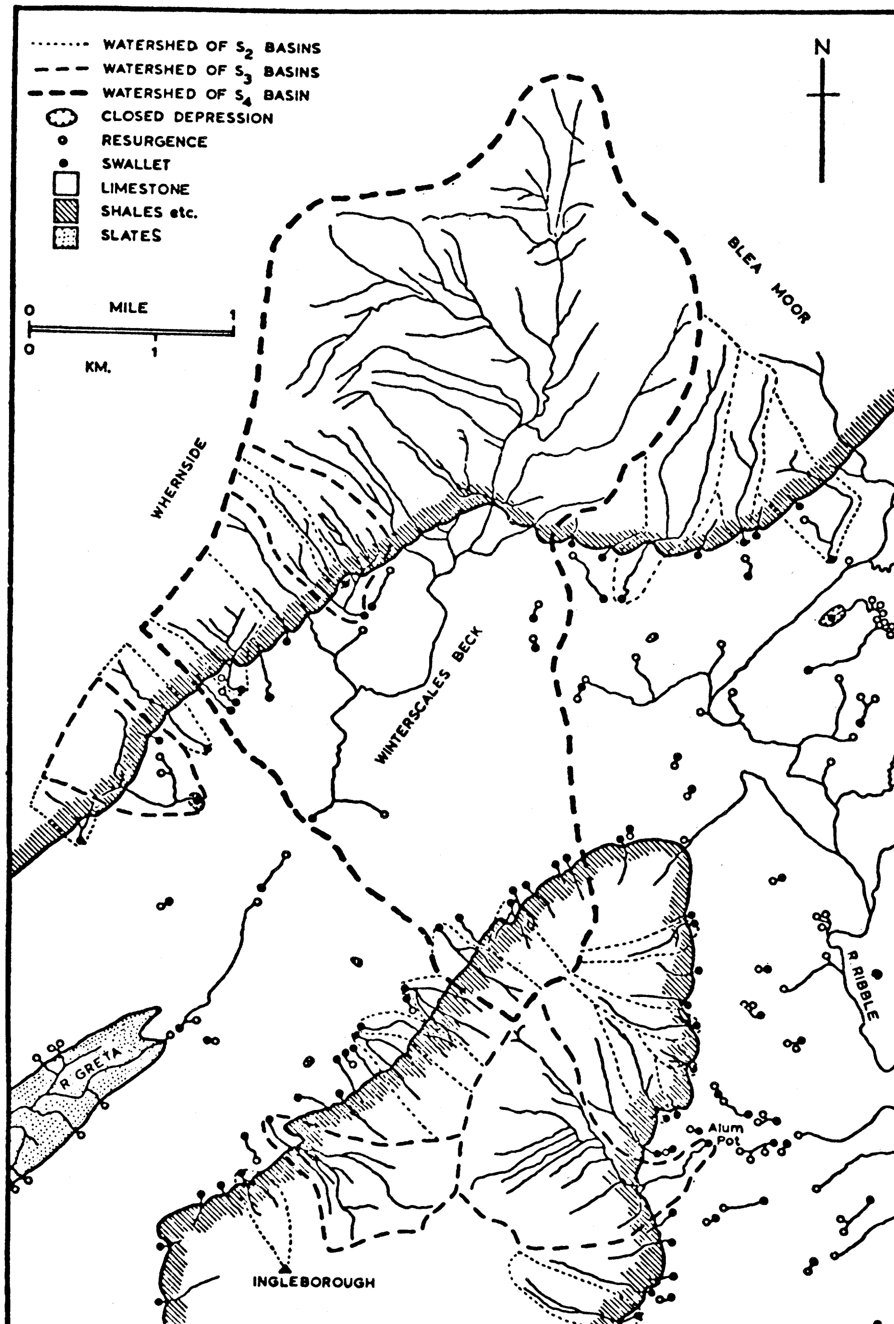

Fig. 2. Some karst features of the Ingleborough District, Yorkshire, England, showing the scarcity of streams in a karst region. [From (*1*)]

Fig. 3. Two new sinkholes recently appeared in a farm in Lebanon Valley, Pennsylvania. The farm is underlain by limestone. [Courtesy of the Pennsylvania Geological Survey]

decrease downward in most carbonate rock terranes, so that the freshwater zone is thin. Old and nearly stagnant brackish water underlies most of the carbonate rock aquifers of the world, and this salty water may present problems in the production of water to individual wells and in the overall development of the aquifers.

2) *Scarcity of surface streams.* Fully developed karst regions are characterized by the absence, or scarcity, of surface streams (Fig. 2) (*1*). The dependence of some biota on streams and the convenient uses that man has made of streams are well known and need not be reviewed here. Where surface streams are scarce or absent, many people must turn to the ground environment for water supplies from wells and for disposal of wastes. The difficulties inherent in these arrangements are discussed at greater length below. The centralization of water discharge as large springs poses subtle management problems because competition arises between users of well water and users of spring water; these problems are not confined to carbonate rock terranes but are likely to be especially acute in them because their ecology and environment are more restrictive or specialized.

͵) *Instability of the ground.* The solution of carbonate rocks and removal of dissolved mineral matter by circulating groundwater produce underground cavities that weaken the structure of the rock above them. Although collapse may be a purely natural event, activities of man such as heavy structural loading and excessive pumping of water from wells accelerate subsidence of the ground in many areas (*2*) (Fig. 3).

4) *Leakage of surface reservoirs.* Where dams are proposed to store surface water in regions underlain by carbonate rocks there is concern as to whether the reservoirs will hold water. The leakage is due to the great permeability of the rocks above the water table. As the water attempts to rise in a surface reservoir it enters various caves and other solution openings which had been dry in the previously unsaturated zone. In such areas it is necessary to inject great volumes of grout in a curtain along the dam so that the particular reservoir will hold water, and this increases the cost of the project. Not only are the test drilling and grouting expensive, but in some fully developed karst areas there is a risk that even grouting will not be adequate to ensure the success of the reservoir.

It is possible to take advantage of the situation, however. In Yugoslavia, for example, a new dam with a grouting curtain about 9 kilometers long was designed for a reservoir capacity that included the groundwater backed up behind the curtain. Not only was the reservoir volume thus greatly increased, but the water stored in the solution openings was far less subject to losses by evaporation.

5) *Unreliable waste-disposal environment.* In general, carbonate terranes are not considered to be satisfactory areas for disposal of wastes into the ground. If the permeability of the carbonate rocks is low the rocks do not accept waste at sufficient rates, and if it is high they permit the waste to move downward quickly and to be transported rapidly to some point of discharge without time for the waste to be oxidized or otherwise purified. The poor capabilities of karst regions for waste disposal are worsened by the thinness of the soil zone. Thick but moderately permeable soils tend to sorb many pollutants chemically or physically and to slow the movement of polluted water so that oxidation or some decay mechanism can allow the pollutant to be attenuated. Pollution of karst groundwater from disposal of wastes in the ground and from undesigned leaching of materials at the land surface is common. In many places such pollution seriously threatens the health of the polluting areas and minimizes the development of groundwater in lower places. The large springs that concentrate the discharge of polluted groundwater become themselves the focus of water problems to the people who depended on them for potable supplies.

Hydrogeologic Conditions

The following are brief sketches of some hydrogeologic settings of a few carbonate rock regions. The relations of the hydrogeologic settings to the present ecology can be inferred.

1) *Central United States.* In Tennessee, Kentucky, and Missouri there are separate but somewhat similar karst settings. Each is characterized by a slight structural dome which has brought to the land surface Middle Paleozoic carbonate rocks, concentrically surrounded by younger Paleozoic noncarbonate rocks. Topographic relief locally or regionally is not as great as in many karst regions. Sinkholes abound and cuestas tend to define the boundaries between carbonate and noncarbonate rocks. The climate is temperate and humid. The permeability is unevenly distributed, a large percentage of the wells having low yields and a smaller percentage having high yields. Streams are fairly scarce, most of the streams being fed by large springs. Soils are generally thin. Many wells are polluted, chiefly because of effluent from

septic tanks. Locally, the collapse of land into subsurface caverns forms sinkholes, which in the more populated areas may create serious problems for houses, roads, and public utilities.

2) *Puerto Rico and Jamaica.* Tertiary limestones are widespread on both Puerto Rico and Jamaica. Both islands were uplifted many hundreds of meters above sea level during Miocene time, and the limestones have been continuously karstified since then. Because the topographic relief is great and the climate is humid and tropical, solutional erosion and attendant land collapse have resulted in deep sinks and pronounced conical hills, which combine to make the terrane difficult to cross. Soils are thin, especially on upland slopes. The water table is deep below upland areas, and large caverns in the unsaturated zone transmit storm waters to openings, such as sinkholes, in the lowlands, where flooding may sometimes occur. Because the permeability of the carbonate rocks is unevenly distributed, the yields of wells range greatly. Some springs are polluted at times. Large amounts of fresh groundwater are discharged to the sea, while some inland areas are short of water because the runoff quickly infiltrates to the subsurface by way of the intricately dissected surface.

3) *Nullarbor Plain of southern Australia.* The most extensive continuous karst region of the world lies as a raised, but nearly level plain along the south-central coast of Australia. Having been subjected to slow karstification through almost continuously arid conditions since Miocene time, this region has almost no soil and vegetation (*3*). Scattered sinks occur over much of the region. The water table lies only slightly above sea level for thousands of square kilometers, and the groundwater is almost everywhere salty. Among the few living things are low shrubs on the land surface and bats, spiders, and bugs in caves.

4) *Central Florida.* Limestone of Tertiary age in central Florida is near the land surface, where it is on a structural arch. The Tertiary limestone is covered by a veneer of Pleistocene quartz sand and clay and, radially from the arch, the limestone is buried under increasingly thickening deposits. Sinkholes are common, but topographic relief is subdued because surficial sands and clays drape into the sinks. The humid climate, coupled with the low topography, keeps the water table near the land surface. Lakes are common. Solution cavities abound in the limestone, but almost all are below the water table. Problems of land subsidence and stability of lake levels are of increasing concern. The quartz sands and clays on the limestone prevent some problems characteristic of most karst terranes. For example, the soils cannot be removed easily, and the filling of solution cavities with sand has caused a slight reduction in the permeability of the limestone. The slight reduction in permeability is favorable because it permits the aquifer to store more water for local use seasonally and to recharge the artesian part of the system, which extends out radially from the structural arch in central Florida.

5) *Northern Yucatan Peninsula, Mexico.* The northern third of the Yucatan Peninsula, as much as 150 kilometers wide, is an almost level karst plain underlain by nearly horizontal Tertiary limestone. The plain ranges in elevation from sea level on the coast to about 40 meters in the interior. The climate is not arid, but precipitation is seasonal. There are no surface streams. Bare, fluted limestone is exposed over large areas; the limestone is almost everywhere pitted and scarred by solution depressions and small ridges. Because of the high permeability of the limestone, the water table is only slightly above sea level (*4*), and storage of fresh water is limited. The scarcity of soils has retarded farming and may lead to water supply problems in villages. The absence of streams caused the ancient Mayans, as well as the present civilization, to rely on "cenotes," or steep-walled natural wells, in which the water table is exposed at the bottom as a small and often lovely lake.

6) *Northern and eastern Mediterranean region.* The karstic areas of Yugoslavia and Greece are classic examples of conditions in complex topographic and structural terranes. Limestones in the Adriatic region, deposited through much of Mesozoic time, were uplifted, folded, and faulted during the Cenozoic. The upland areas are practically bare, and what little soil there is tends to be concentrated in the valleys. Although the rocks are intricately channeled, the spring rains and runoff are so great that many of these valleys are temporarily flooded in the wet seasons. Streams are scarce in the fully developed karst areas. Groundwater lies deep below the upland areas and tends to be funneled away along large subsurface channels to large springs. These springs may resurge above or below sea level. Enormous quantities of fresh groundwate are wasted as they mix with sea water at submarine springs.

Maintaining Ecological Balance

We often assume that there was a fair degree of ecological balance in all regions of the world before man significantly changed the landscape. Yet in karst regions, more than in many other specialized environments, ecological conditions were already skewed and the biota were developed in special and sometimes erratic ways. The scarcity of soils, the scarcity of water at the land surface, and the rugged terrane are not conducive to a flourishing and expansive environment. Man has added to the already skewed situation by deforesting hilly karst, which in turn has accelerated the erosion of the scanty soil, and by polluting the groundwater in many places. The question is whether nan will continue to compound the problems of the karst environment or whether he will adjust to and improve it.

Some of the problems relating to climate seem almost insurmountable. For example, the immense karst desert of Nullarbor Plain is simply waterless and uninhabitable. To expand the development of organisms significantly seems impossible.

The difficulties of rugged topography, such as that in the Cockpit Country in Jamaica and that in northern Guatemala, can be partly overcome—insofar as man's access and habitation are concerned—by building modern roads through the regions. It would be inappropriate here to debate the question of building roads.

Some restoration of soils in less arid karst regions can be made through reforestation, such as that attempted in parts of Yugoslavia. Locally in some karst areas there is an "inversion of soils," more soil being trapped in sinkholes and solution openings below the land surface than occurs on the land surface. Recovery of some of the subsurface soils to distribute them again on the land surface may be possible if satisfactory recovery techniques can be developed.

The hydrologic problems in a karst area need to be considered both separately and in conjunction with other aspects of the environment. For example, heavy local pumping of groundwater in one area may cause local catastrophic land subsidence elsewhere. A problem that man can partly solve is the elusiveness of groundwater and the difficulty of capturing it in karst regions. In interior karst regions groundwater tends to discharge as large springs that lead to freshwater rivers. In coastal karst regions, however, freshwater springs and rivers may be scarce; large volumes of fresh water move directly into the sea. The high and uneven distribution of permeability in karst regions makes this waste to the sea a serious problem because it deprives man and other life of the nourishment that water in the right places brings.

Attempting to salvage this fresh water that is wasting to the sea is not likely to have offsetting ecological problems. Yet, the delicate natural hydrological balances within a karst region can easily be disturbed, and advantages gained by altering the hydrology may be offset by various detrimental effects.

Changes in hydrological balances are not unique to karst regions, but karst regions are more sensitive than other regions and the counteracting problems may be especially severe. It is necessary to understand environmental relationships, particularly those involving hydrology, to determine whether some actions by man are warranted. As a result of increased studies evaluation of these hydrological problems is coming into better focus. There is a need for improved knowledge of this important subject, which can be applied to the development of carbonate rock terranes for human use.

Fortunately, we can take specific action to maintain and upgrade the ecology of carbonate rock regions without waiting for additional field data to be collected. Our review of some hydrological relationships indicates that the ecological problems have generic solutions. These relationships have patterns that can be cast in terms of rules and principles. For example, good circulation of subsurface water leads to appreciable solution of the rock, solution leads to overall high permeability, and high permeability tends to lead to a water table well below most of the land surface and to scarcity of water on the land surface. Such general relations and tendencies need to be combined with pertinent specific data for a particular region or area. For ecological evaluations, it would be foolhardy to treat each carbonate rock terrane solely on its own merits, and to collect masses of data before decisions on the ecology are made. The data available are sufficient to give good first-round approximations to the solutions needed. Successively better approximations can be made as more data are considered, but in no case do we need to wait until new data are collected.

Summary

Climate exerts a universal dominant influence on ecology, but processes of karstification have an equally high ecological influence in carbonate rock regions. Development of karst features depends greatly on the degree to which water containing carbon dioxide has been able to move on and through carbonate rocks and to remove some of the rock in solution. Distinctive features of many karst terranes include scarcity of soils, scarcity of surface streams, and rugged topography; less distinctive are the highly permeable and cavernous rocks, especially at the shallow depths. This high permeability gives rise to many practical problems, including (i) scarcity and poor predictability of groundwater supplies, (ii) scarcity of surface streams, (iii) instability of the ground, (iv) leakage of surface reservoirs, and (v) an unreliable waste-disposal environment.

Natural karst processes in some carbonate rock regions have caused a greater restriction in the development of biota than man can ever be sus pected of causing.

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Assembly of Bacterial Ribosomes

In vitro reconstitution systems facilitate study of ribosome structure, function, and assembly.

Masayasu Nomura

The structure of ribosomes is complex. There are two ribosomal subunits, named according to their sedimentation coefficients. In *Escherichia coli*, the smaller, 30*S* subunit consists of one 16*S* RNA molecule and about 20 protein molecules. The larger, 50*S* subunit consists of one 23*S* RNA molecule, one 5*S* RNA molecule, and about 30 to 35 protein molecules (*1–3*). The development in recent years of systems permitting the reconstitution of ribosomes in vitro has advanced considerably our knowledge of the structure, function, and assembly of these organelles. Because the reconstitution of 30*S* subunits was achieved first and because our knowledge of this subunit is much more extensive than our knowledge of the 50*S* subunit, I center my discussion on the 30*S* subunits and refer only briefly to the 50*S* subunits; other aspects of ribosome research have been discussed more extensively elsewhere (*1–4*).

Assay of Ribosomal Functions

The activity of ribosomes and reconstituted ribosomes is routinely assayed by means of cell-free polypeptide synthesizing systems that are directed by natural messenger RNA or by synthetic mRNA such as polyuridylic acid. In addition, several partial reactions are used to assess the activity of ribosomes and reconstituted particles. These reactions include the binding of formylmethionyl-transfer RNA directed by