STATICS AND DYNAMICS OF WATER IN THE SYRO-LEBANESE LIMESTONE MASSIFS

by

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ARIDITY AND HYDROGRAPHY

Of the various countries of the Middle East, the Lebanon and Syria exhibit the whole range of climatic and hydrographic degradation. Aridity becomes increasingly great from the Mediterranean littoral towards the interior, promoted by the coastal mountain barrier which intercepts the moist air currents and prevents their penetration into the hinterland. Thus, the climate passes through all the stages from the Mediterranean to the Mesopotamian desert type as the moderating influence of the sea becomes progressively less. Taken as a whole it is a climate of extremes. The year has two main seasons—a long—indeed a very long—summer, in which high temperatures are encountered as soon as the coastal range is left behind and a brief but well-marked winter distinguished not by the frequency but by the volume and violence of the rainfall. Beyrouth, for instance, receives more precipitations in three or four months (900 mm.) than Paris does in the whole year (530 mm.) and at certain mountain stations (Djezzime, Le Krey, Machghara) there is an average of 400 mm. of rainfall in February alone.

Inland from the littoral and the mountain belt, where vegetation is varied, there is a rapid transition to cultivated steppes with villages here and there, then abruptly to desert steppe, a pastoral area inhabited by wandering tribes, and lastly to the true desert. With the coastal ranges to extract their moisture the winds dry out rapidly in their passage to the interior, changing almost without an intermediate stage from powerful humidifying factors on the coast to even more potent drying agents in the hinterland.

Study of the deficit of flow of certain streams (Litani, Afrine, Kara-Sou) has led us to the conclusion that flow begins at a degree of pluviosity of between 100 mm. and 200 mm., and not the figure of 250-500 mm. previously agreed on by geographers for this area. This point is of importance as it explains the peculiar behaviour of the streams in Syria and Lebanon.

In the writer's view the essential reason for the relatively low pluviosity-flow ratio in Syria and Lebanon is that rainfall is concentrated into a few months of the year only.

During these few months rain is abundant and precipitations take the form of heavy and even torrential downpours favouring surface drainage. All the same the geological formations of the catchment basins are Jurassic and Cretaceous, limestones and karst in the massifs, so that almost all these basins exhibit two mutually incongruous phenomena—rapid run-off as a result of the heaviness of the downpours and intense percolation in the fissures of the limestone massifs.

The present hydrological pattern is the result of the interaction of these two factors; there are few perennial streams and the supply of primary importance is the ground water in vast "storage massifs". Springs are few but powerful and it frequently happens that the water of a whole massif of great size is discharged from one or two springs only. Thanks to the deep-lying supplies which feed them, the rate of flow of these springs is high and unaffected by the variation between seasons or even years.

The effect of the first factor, as a result of which streams flow when rainfall reaches only 100-200 mm., is to favour evaporation.

The effect of the second is to prevent direct evaporation by storing water in the deep strata of the massifs.

Hence it would seem that the deficit of flow must be determined by atmospheric evaporation occurring at the same time of year as atmospheric precipitation, i.e. in the rainy season, since the only water left after the rainy season is the deep-lying ground water which escapes evaporation. The conclusion appears to be that the effect of the sudden contrasts of the climate must be very great, to have the effect of determining, mainly in the winter, the deficit of flow.

It follows that the factors most influential in differentiating the major hydrographic zones of the country are necessarily the climatic, more particularly temperature and pluviosity, and in fact the progressive deterioration of the climate towards the interior is matched by a corresponding degeneration in the hydrology. Inland from the coast to the desert steppes of the interior, four main hydrographic zones of unequal size can be identified in ascending order of aridity:

1. A zone of permanent streams draining to the Mediterranean; the area of the coastal torrents of which the larger never run dry.
2. A zone where drainage is seaward (Orontes, Litani) or inland (Jordan) according to the relief—i.e. the area of the axial depression parallel to the coast forming a corridor between the Lebanon and anti-Lebanon chains and containing the upper reaches of the Litani and Orontes. These are more considerable rivers than the coastal torrents, and both present the anomaly of mountain rivers on the border of the steppe which are neither torrents nor wadis but tranquil and regular streams with abundant water throughout the year. Both rivers break abruptly towards the Mediterranean, the Litani via a capture elbow, arising from one of the key faults of the earth's surface, which has diverted it from the Dead Sea basin, and the Orontes by a similar elbow which diverts it from Lake Amouk near the crossing point of the major "African" fault and a local fracture.
3. A zone of inland drainage on the borders of the desert where the streams run into closed basins—e.g. the Koueik bowl at Aleppo, the salt lake of Djaboul, the Damascus basin with Lakes Euteibé and Hidjaneh, respectively the base levels of the Nahr Barada and the Nahr El A'ouadj; finally, divided from the last-named by the Hauran volcanic system, the Jordan basin connected with the vast Dead Sea depression, the lowest-lying area on the land surface of the earth (393 m. below sea level). This zone is watered by streams fed by great storage massifs—Hermon (A'ouadj, Jordan), the Djebel-Druze, the Hauran and the south-eastern extremity of Hermon (Yarmouk) and the Anti-Lebanon (Barada). The Yarmouk is the final limit of the system of inland drainage from the borders of the eastern desert zone.
4. The desert proper, a waterless zone with wadis bearing witness to an active hydrology in the past but now passing through an arid cycle which has halted their development.

From the foregoing outline it will be clear that surface-water resources are poor, confused and seasonal, the basins drained even by the permanent streams being replenished with rain or snow during the short intensive winter season only. However, against all the visible probabilities, their discharge is maintained even in summer, thanks to the geology of the region by which the excesses of its climate are corrected: the Jurassic and Cretaceous limestones serve as "storage massifs" to catch and conserve the surplus rains of the winter, and the water is subsequently fed back by springs which, if few, are of immense volume. The combination of these two facts—the permeability of the terrain and the conservation thereby of the excess rainfall of the winter alone—accounts for the continued flow of the permanent streams during the long dry season of the Middle East and also allows of the practice of irrigated agriculture. The area would be more parched if its soil had been less permeable.

The influence of aridity on the hydrography can be grasped by comparing indices of aridity with deficits of flow. Plotted on the map, the curves of equivalence of aridity and coefficient of flow respectively will be found not only to coincide but to delimit major hydrographic zones which conform to the major structural features, thus illustrating the combination of the factors of relief and climate in influencing the hydrography.

A simple formula suggested by E. de Martonne and called by him the "index of aridity" is the following:

$$a = \frac{P}{10 + T}$$

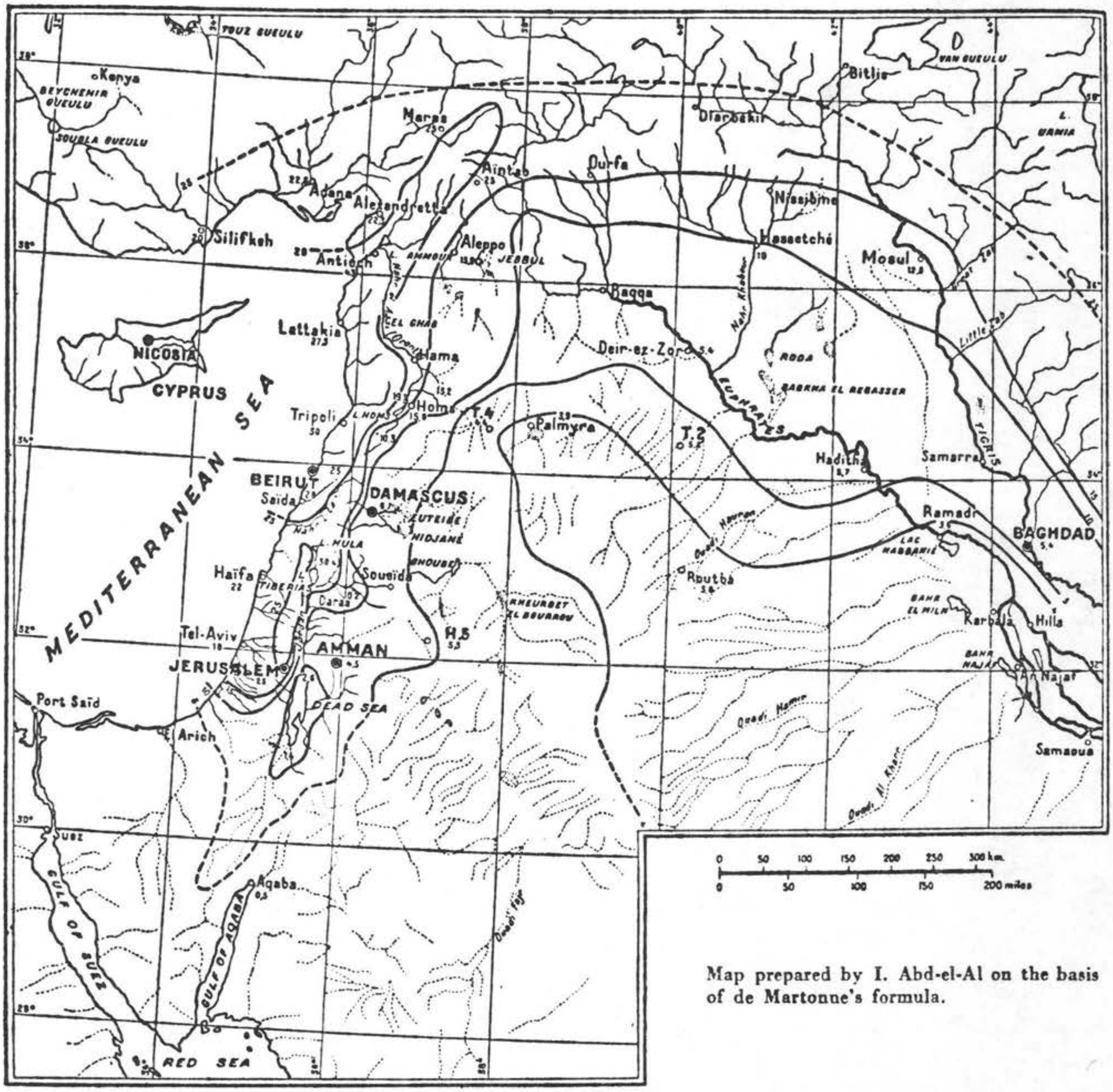
in which P is the pluviometric index or module (total annual precipitations) and T the mean annual temperature.

As Coutagne has pointed out, this simple formula is of real hydrographic significance. Deficit of flow is, in the final count, the effect produced by the evaporative action of the atmosphere on the soil. For the main Syro-Lebanese regions it is represented by the following formulæ:

Affluents of Orontes:	
Kara-Sou	$D = 15.5\,(10 + T)$
Affrine at Bassout	$D = 14\ \ (10 + T)$
Affrine at Midanki	$D = 13.7\,(10 + T)$
Litani at Mansourah	$D = 15.5\,(10 + T)$

If $P = D$, the index of 15 represents on average the degree of pluviosity necessary and adequate for flow to occur, which is a fact of some importance: it makes a difference between the countries of the Middle East and those of the temperate zone where the minimum pluviosity index for surface flow is 20. The curves of equivalence of aridity indices have been plotted on the 1/4,000,000 map and the degree of coincidence between them and boundaries of the major hydrographic zones enumerated above is extremely striking. With the exception of the Jordan above Lake Tiberias, a separate unit in which the relief has determined the drainage, and of the tectonic gulf of the Dead Sea, an enclave with an index of pluviosity as low, relatively as its altitude, the 15-index curve corresponds almost completely to the watershed between the areas of seaward and inland drainage in the west. Thence it runs northward up the country and swings east via the sources of the Khabour and the Balikh, Syrian tributaries of the Euphrates, fed by water from outside the area. In classical Mesopotamia incidentally we have

Middle East. Relation between aridity and the hydrographic system

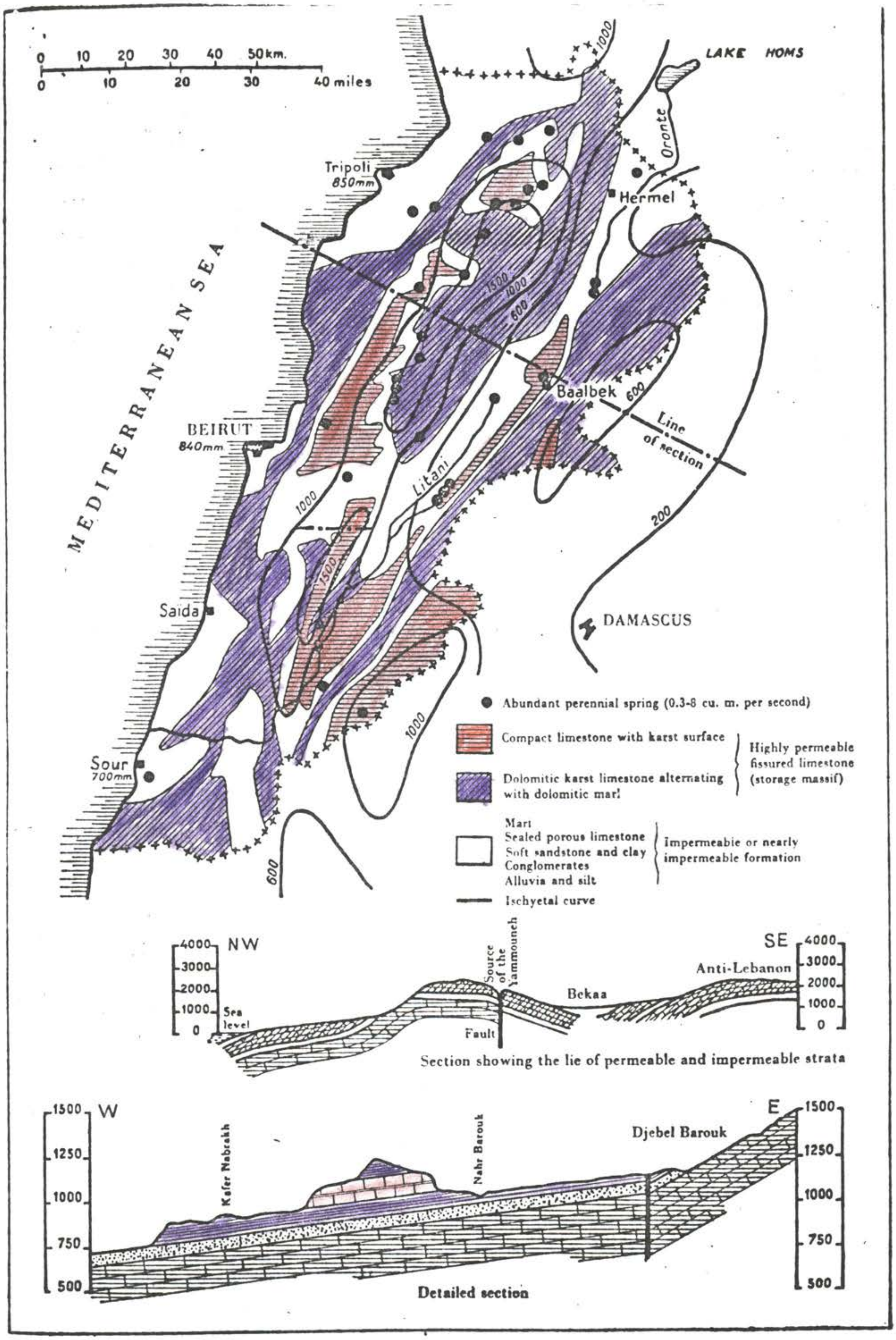


Map prepared by I. Abd-el-Al on the basis of de Martonne's formula.

the striking anomaly of an area without surface-water sources and drainage of its own, but through which there passes the largest volume of water of any country in the Middle East.

The 25-index curve encloses the whole of the basin of Lake Antioch in the north and in the main follows the ridge bounding the valleys of the Litani and the Orontes but swings eastward from the latter river at the northernmost point of the Ghab marshes, as a result of the moist sea air which the Amanus corridor funnels into whole lower valleys of the Orontes and the Kara-Sou. To the south the curve swings towards the Mediterranean roughly along the line of the watershed of the Litani basin. The more favourable coastal conditions prevail from the mouth of the Litani to the estuary of the Orontes.

Aridity increases along the Palestine coast south of the mouth of the Litani, with the exception of a 25-index enclave running along the highlands from Galilee in the north to Judea in the south, parallel to the Ghor trough and balancing the arid enclave of the Dead Sea.



Hydrological map of the Lebanon

The Aleppo bowl in the north and the Yarmouk valley in the south lie between the 15-index and 10-index curves.

The 5-index and 10-index curves are the respective boundaries of the Dead Sea Basin, in which, it will be noted, the Damascus bowl is included climatically. The basin appears to extend to the north as far as T4 between Homs and Palmyra where the run of the curves suggests a col dividing the basins of the Dead Sea and the Euphrates.

The 4-index and 5-index curves delimit a waterless closed basin opening out southwards while the 4-index curve marks a clear-cut western boundary to the Euphrates basin.

THE HYDROLOGY OF THE LEBANON

Most of the Lebanon is mountainous, consisting in the main of highly permeable rock formations, e.g. compact limestones with karst surface (1,160 sq. km. of a depth of 1,000 m.); dolomitic karst limestones alternating with dolomitic marl (5,130 sq. km., to a depth of 700 m.).

These limestone formations are important storage massifs and act as reservoirs to maintain the springs during the dry season.

The water infiltrating into the fissures of the limestone does not sink right down but follows the irregular and confused course of the underground conduits without spreading uniformly through the bottom strata of the mass. If these conduits are cut by a topographic surface, e.g. in a valley bottom, the water emerges in the form of a powerful spring. However on occasion the limestones plunge below the level of the adjacent valleys or depressions, in which case the recharged water fills the deep-lying fissures and regurgitates at a low-lying point where the lower-fissured strata are saturated because they can absorb no more.

Between these two thick and lithologically different limestone horizons, there is a complex series comprising sandstones, sealed limestones, clays and marls forming a level of low permeability (permeability decreasing from bottom to top) and favouring the emergence of a multitude of small springs. The roof of this series is permeable and stops the percolation of the water which has infiltrated into the overlying dolomitic limestone massif, returning it to the surface as ordinary springs.

It will be clear from this outline that as regards ground-water hydrology the Lebanon is divisible into two distinct zones:

1. The area of highly permeable "storage massifs" comprising two zones of 1,160 and 5,130 sq. km. respectively—a total of 6,290 sq. km. Here there are literally underground rivers and gigantic water reserves while the surface stratum is waterless and unfit for any crops during the long summer season. The whole of this zone is remarkably rich in ground water. The depth of the hydrostatic level is variable from region to region within limits apparently of 200 m.
2. The zone of impermeable or nearly impermeable strata, 4,210 sq. km. in area, in certain regions of which such as the Bekaa, the littoral plain of Beyrouth and Saïda—true water-tables are formed which could profitably be exploited.

GEOLOGY AND SURFACE FLOW

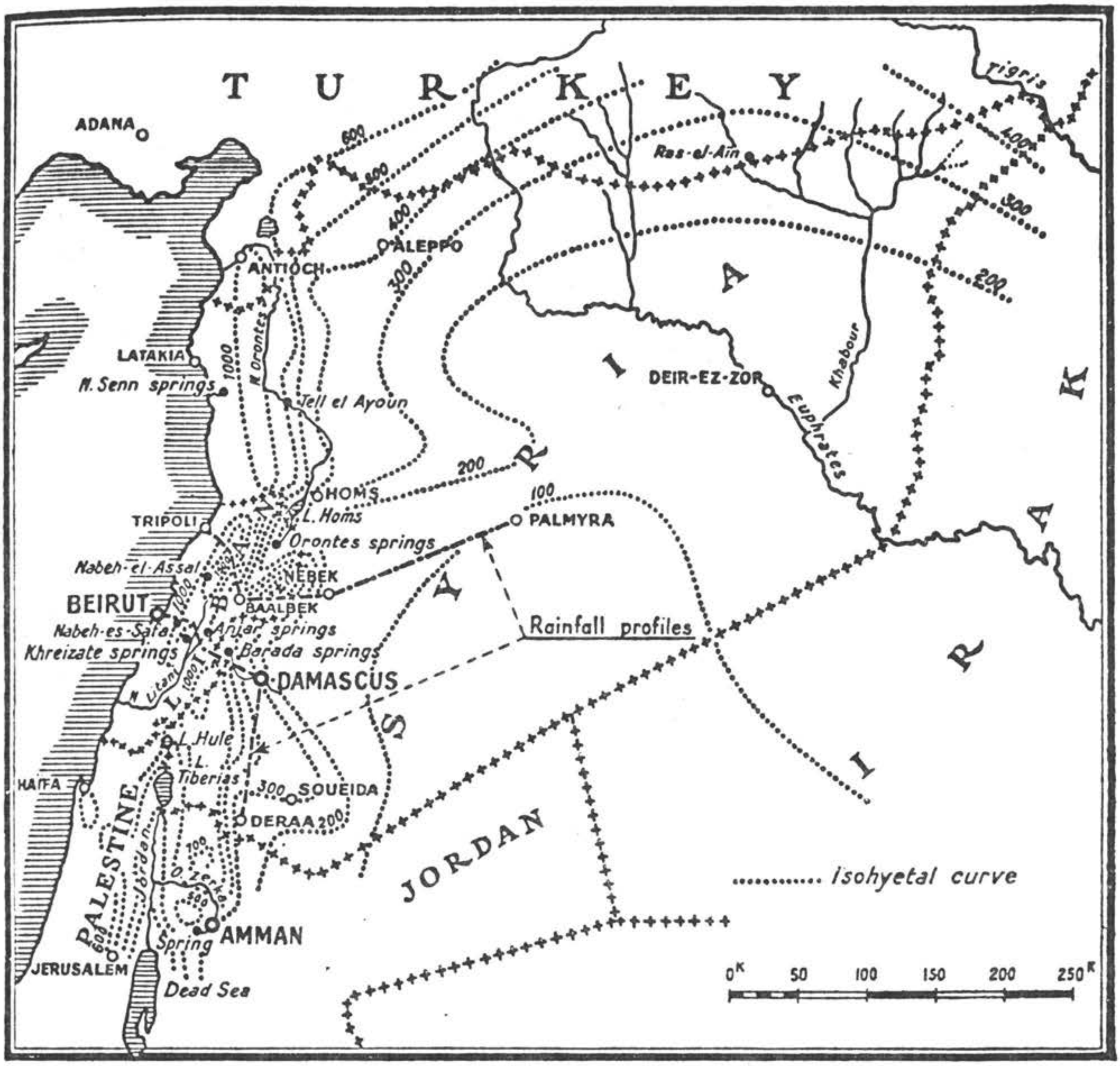
The Jurassic and Cretaceous limestone massifs forming the mountain chains are fissured and of karst type and their capacity for the absorption of rain water is high. Hydrologically the development of karst conditions has a moderating influence through the formation of large water reserves which do not dry up even after six to seven months of absolute drought.

Structurally the country is one of large masses, and involvement in the greatest of the movements of the earth's crust has left it with an abrupt relief. The violence of the rainfall, while favouring run-off also markedly intensifies the karst régime and while a rainfall of 100 mm. suffices to set the torrents flowing they dry up, with few exceptions, after the rainy season.

The parallel and balancing Lebanon and Anti-Lebanon ranges are 170 km. in length approximately, by 30 km. broad. The limestone of which they consist is broken by fissures large enough almost to count as caverns and karstic erosion has cut subterranean passages several kilometres in length. Examples are the Jehita Grotto feeding the Nahr-el-Kalb coastal torrent and the grottos of Kaphka and Kadicha which, though shorter, feed the Nahr Ibrahim and the Nahr Abou-Ali, the most fully developed of the coastal torrents.

The essential structural feature of the Lebanon range is the great longitudinal fault running along its eastern face and prolonging the faults of the Dead Sea cleft. Along the length of the fault lie a number of small

Contour map



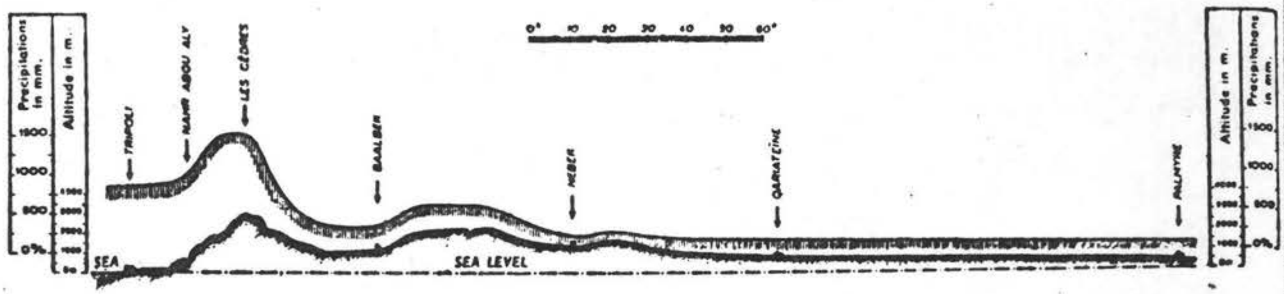
closed basins, the finest of which, Yammouneh, is a temporary lake during the annual thaw.

The Anti-Lebanon range is cut obliquely by two faults which form the boundary of the Hermon massif. There is however less faulting in the Anti-Lebanon than in the Lebanon and its chief characteristic is the superposition of faulted and folded structures. It is a stage in the transition to the finely and slightly folded structures of the hinterland.

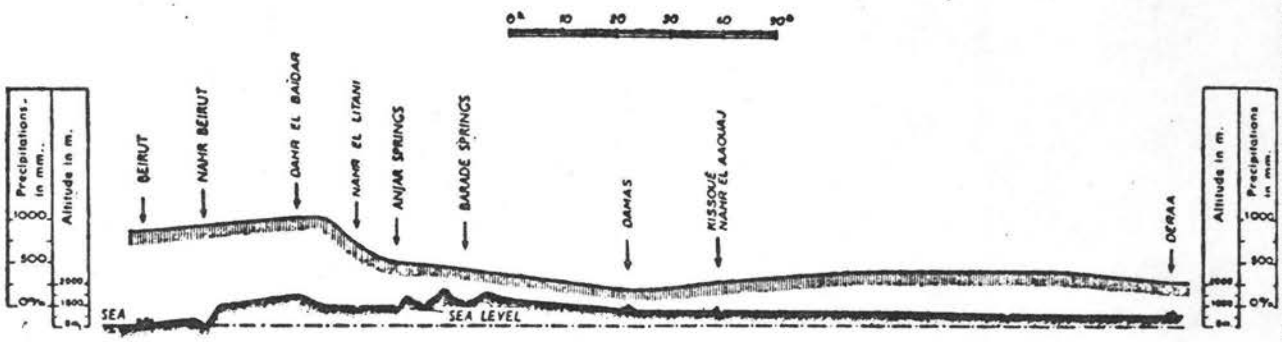
The two massifs are thus clearly twin horsts of the same proportions and similar topographically and geologically. It follows therefore that the heavy downpours must have analogous effects on water movement in either massif, due to intensive karstification made uniform by the violence of the rainfall on both chains.

Study of the principal springs shows that the subterranean channelling in the limestone has extended to great depths and over wide areas, resulting in the formation of very large reserves of water. In the majority of cases these springs are of the Vaucluse type and emerge, not where they meet an impermeable horizon, but at the lowest point of a massif as though they were acting as overflows, either because the fissures in the limestone can contain no more water or because fissuring ceases in the lower strata.

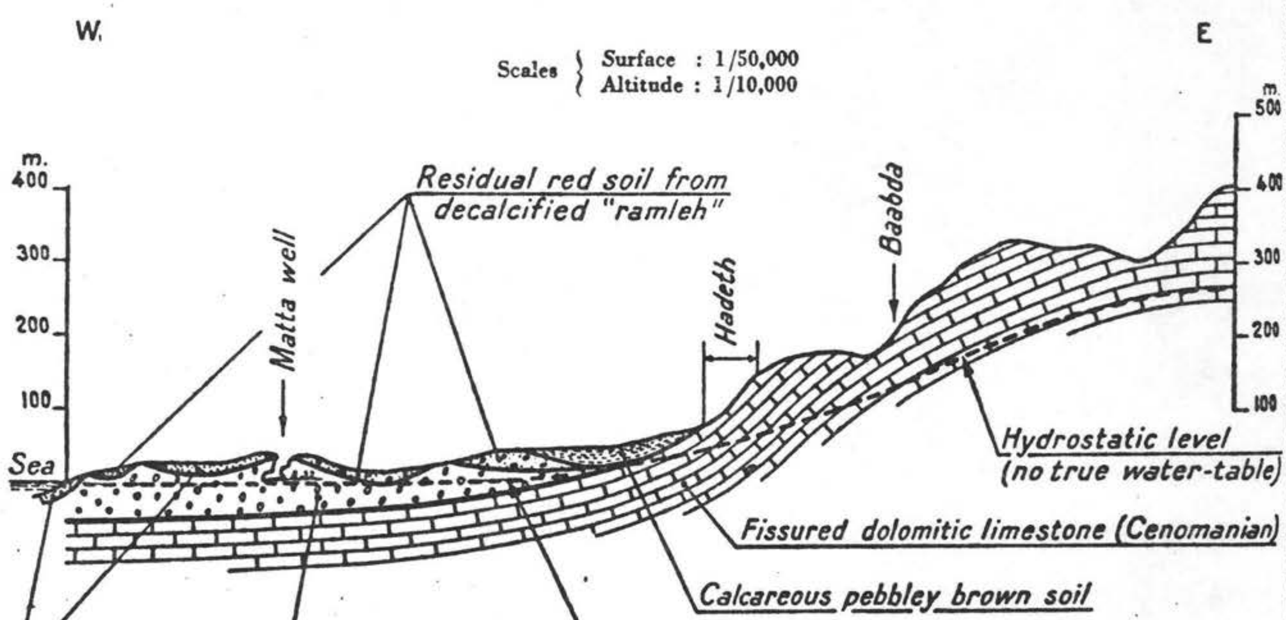
Section along the Tripoli - Baalbek - Palmyra line



Section along the Beyrouth - Damascus - Deraa line



Circulation of water in sandstone formations (Beyrouth district)



ANTI-LEBANON MASSIF

Typical of the anti-Lebanon springs are the group on the western face feeding the Litani.

The most important is the Anjar spring which draws its water from a Cenomanian plateau.

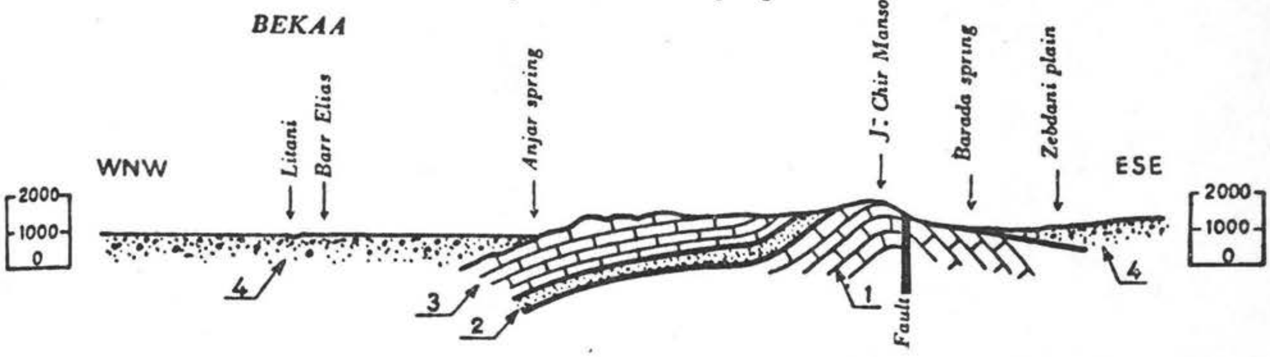
On the eastern face is the high-lying Barada spring fed by a Jurassic crest. The curves of exhaustion, residual volumes and useful discharge for both springs are shown below.

The equation of the curve of subsidence in neutral conditions—i.e. in absence of any rainfall or snow on the massifs—is of the hyperbolic form

$$q = \frac{q_0}{(1 + at)^2}$$

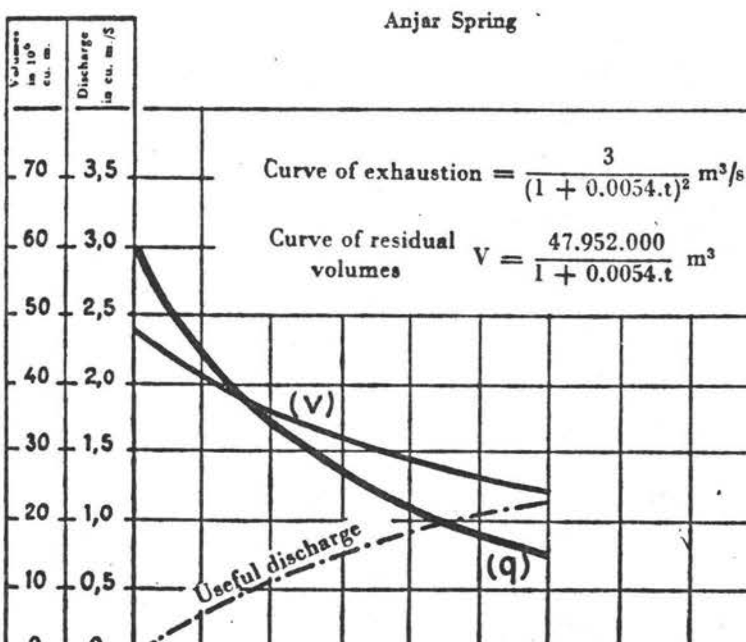
Here q_0 is the saturation discharge, i.e. the highest discharge noted after the cessation of surface run-off. The factor a is the co-efficient of exhaustion of the spring and its value is in inverse proportion to the amplitude of the reserves on which the spring draws.

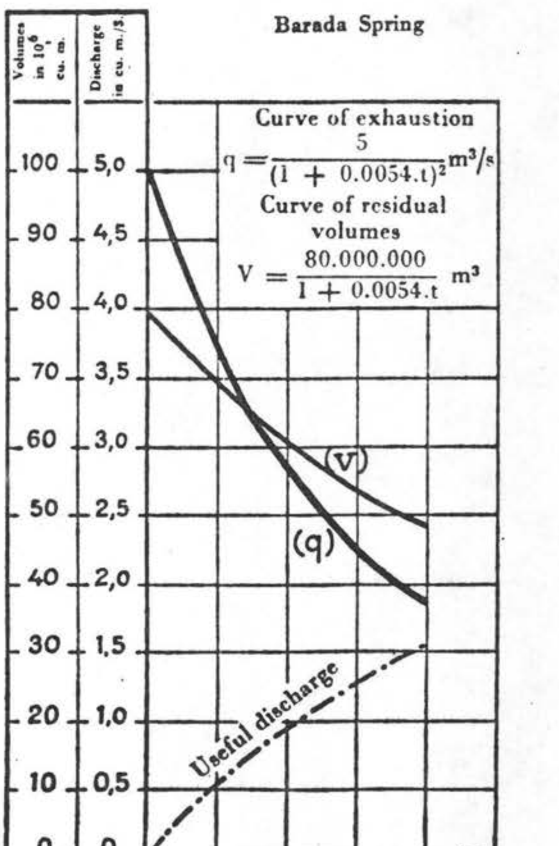
Anjar and Barada Springs



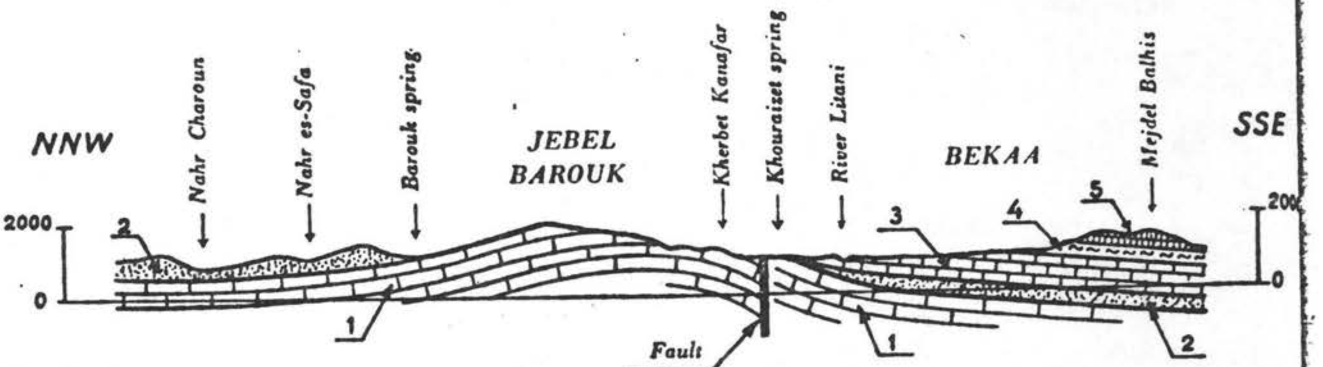
Section illustrating the formation of the springs

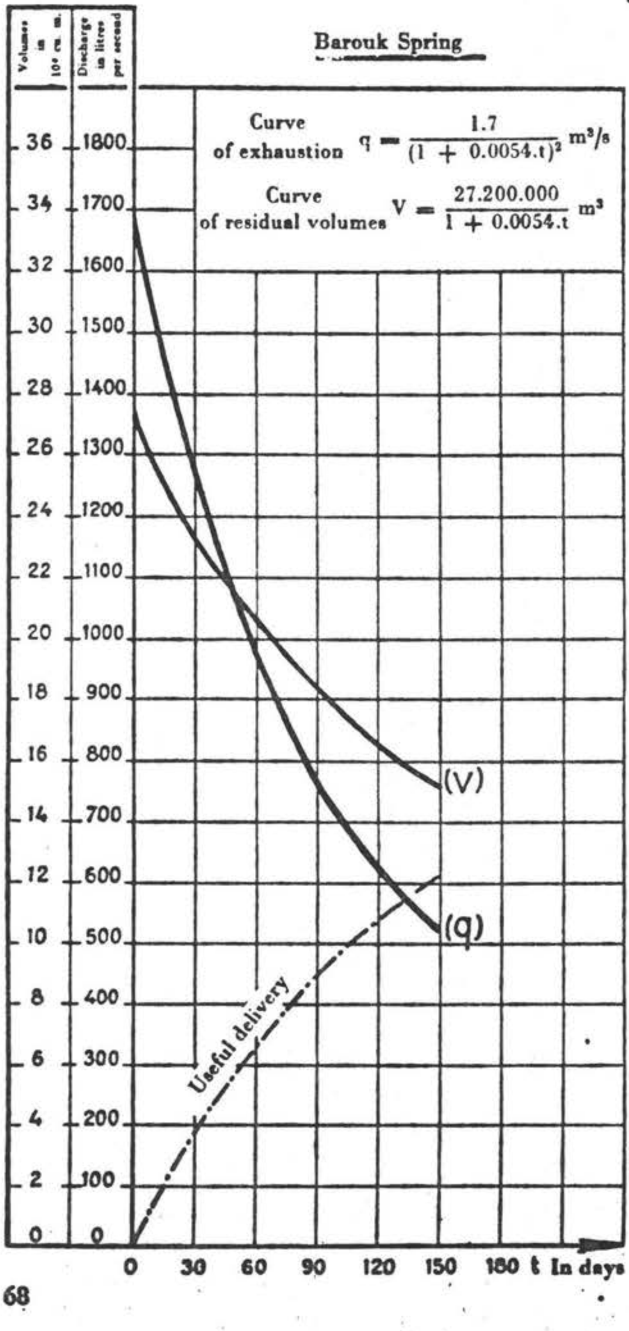
1. Fissured limestone massif (middle Jurassic).
2. Sandstones and clays with limestone and marl benches (lower Cretaceous).
3. Fissured limestone massif (Cenomanian).
4. Silts (Quaternary).





Barouk and Khouraizat Springs

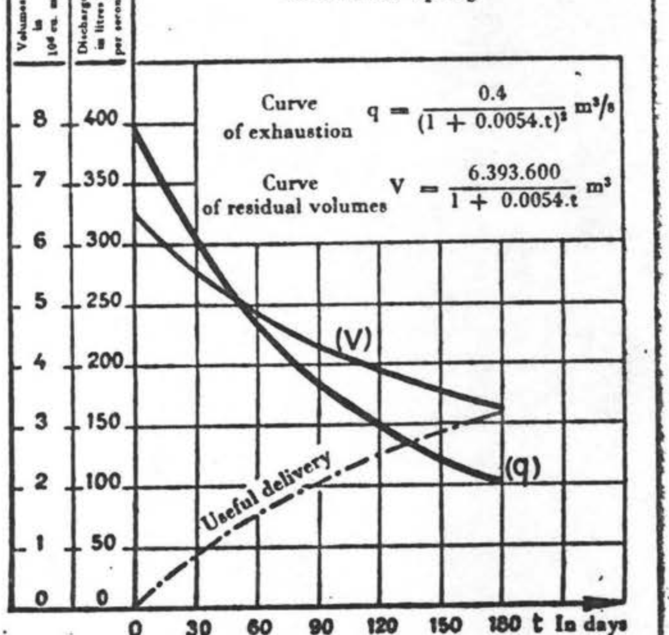




Section showing the formation of both springs

1. Fissured limestone massif (upper Jurassic).
2. Sandstones and clays with limestone and marl benches (lower Cretaceous).
3. Fissured limestone massif (Cenomanian).
4. Chalky withe marls (Senonian).
5. Marls, limestone and white subrecifal limestone (middle Eocene).

Khouraizat Spring



For the plotting of the curve of residual volumes the starting point is the equation

$$q = -\frac{dv}{dt}$$

which gives

$$V = \frac{q_0}{a(1 + at)} = \frac{V_0}{1 + at}$$

taking

$$\frac{q_0}{a} = V_0$$

The following relations were arrived at:

Anjar spring:

$$q = \frac{3}{(1 + 0.0054\, t)^2}, \text{ in cu. m./s.}$$

$$V = \frac{47{,}952{,}000}{1 + 0.0054\, t}, \text{ in cu. m.}$$

Barada spring:

$$q = \frac{5}{(1 + 0.0054\, t)^2}, \text{ in cu. m./s.}$$

$$V = \frac{80{,}000{,}000}{1 + 0.0054 t}, \text{ in cu. m.}$$

The same co-efficient of exhaustion applies for both springs. The usable reserves compensating subsidence amount to about 48 million cu. m. for Anjar and 80 million for Barada.

The capacity of the storage massifs can be expressed in terms of the angular co-efficient of the tangent to the curve of exhaustion at the starting point.

The relationship of the angular co-efficients of the tangents to the curves of Anjar and Barada is:

$$\frac{m_A}{m_B} = 0.6$$

It can be verified that if t_A and t_B represent the duration of subsidence to the point of minimum flow for Anjar and Barada respectively,

$$\frac{t_B}{t_A} = \frac{m_A}{m_B}$$

The rate at which the Anjar spring dries up is about two-thirds of that for Barada: as the geological section shows, the former has a more extensive storage massif.

The equality of the co-efficients of exhaustion indicates that the underground water circulation in the karst formations of the Anti-Lebanon massifs is a single system.

LEBANON MASSIF

On the slopes of the parallel Lebanon massif are the Khoureizat and Barouk springs.

The characteristic hydrological curves of both are given opposite.

In the case of the Barouk spring the storage massif is a large Jurassic vault, whereas the Khoureizat spring emerges on the throw of the Lebanon fault and its storage massif is less clearly defined. The probability is that this spring is fed, and its period of subsidence prolonged until the autumn, by the water circulating through the fracture. The Barouk spring emerges through numerous cracks where the Jurassic limestone massif meets the Cretaceous foothills. Here it is the difference in the lithology of the strata which determines the emergence of the spring.

The curves may be expressed by the following equations:

Barouk:

$$q = \frac{1.7}{(1 + 0.0054\, t)^2}, \text{ in cu. m./s.}$$

$$V = \frac{27{,}200{,}000}{1 + 0.0054\, t}, \text{ in cu. m.}$$

Khoureizat :

$$q = \frac{0.4}{(1 + 0.0054\, t)^2}, \text{ in cu. m./s.}$$

$$V = \frac{6{,}393{,}600}{1 + 0.0054\, t}, \text{ in cu. m.}$$

The co-efficient of exhaustion—0.0054—is the same for these springs as for Anjar and Barada.

The relationship of the angular co-efficients to the tangent of the curves is as follows:

$$\frac{m_B}{m_K} = 4.2$$

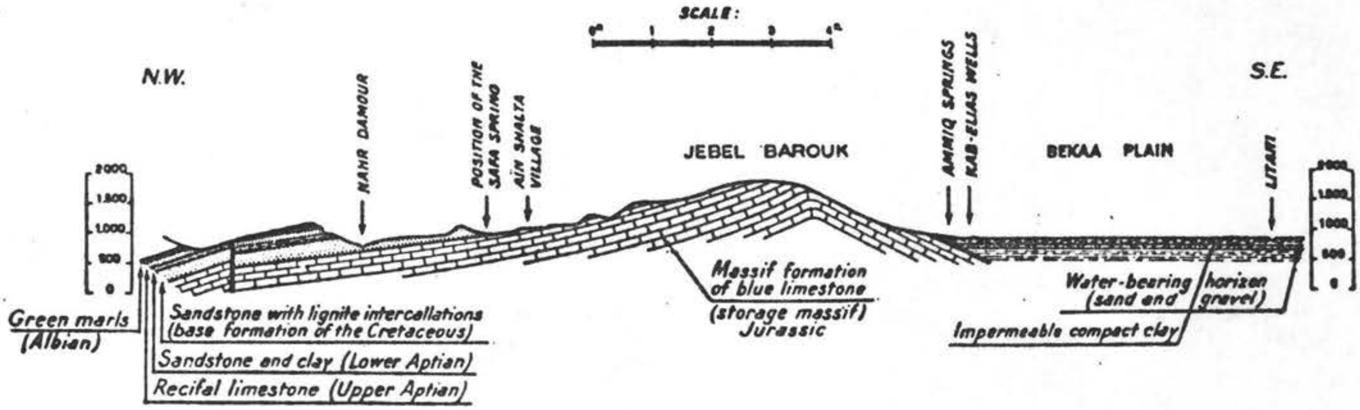
The rate of drying up is here the same for both springs, despite the fact of the Barouk formation being fed from a storage massif much more extensive and well defined than that of Khoureizat.

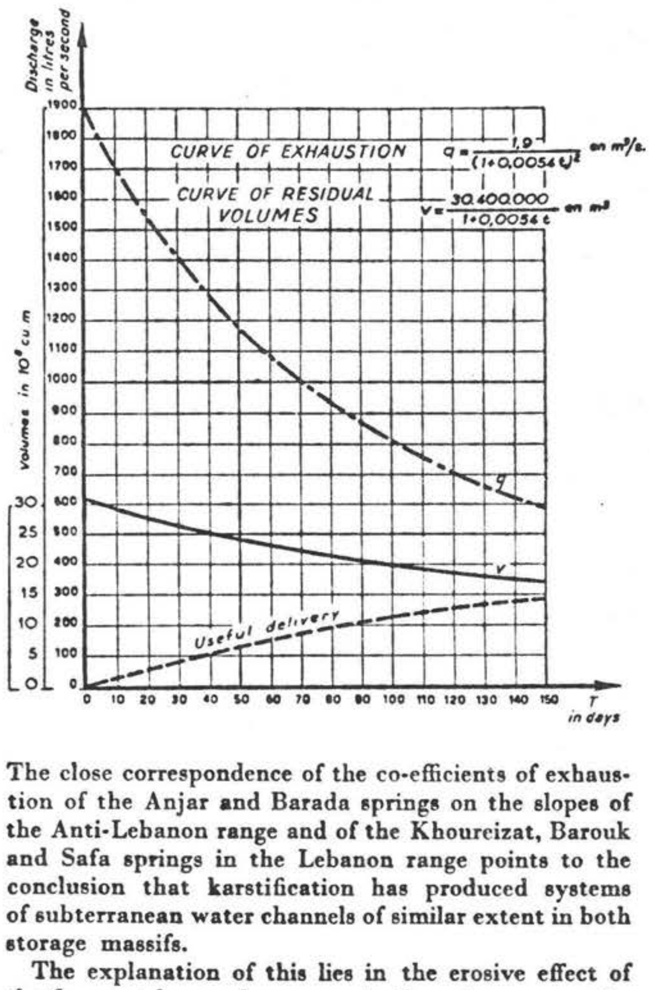
Another type of spring characteristic of the Djebel Barouk massif is the Safa spring, fed by the same hydrological system as the Barouk spring. The rule of subsidence here is given by the equations

$$q = \frac{1.9}{(1 + 0.0054\, t)^2}, \text{ in cu. m./s.}$$

$$V = \frac{30{,}400{,}000}{1 + 0.0054\, t}, \text{ in cu. m.}$$

Section showing the mode of emergence of the Safa Spring





The close correspondence of the co-efficients of exhaustion of the Anjar and Barada springs on the slopes of the Anti-Lebanon range and of the Khoureizat, Barouk and Safa springs in the Lebanon range points to the conclusion that karstification has produced systems of subterranean water channels of similar extent in both storage massifs.

The explanation of this lies in the erosive effect of the frequent heavy downpours in the rainy season, the concentration of rainfall into a few months of the year only and its high seasonal volume being factors of such potency as to have caused a similar degree of development in either storage massif of the system of subterranean conduits, wells, abysses, and caverns where the water which has percolated through the limestone accumulates. Such equality in storage capacity is clearly indicated by the regime of the springs studied in each.

Further there are numerous analogies in the mechanisms of these springs' resurgence. They are overflow springs whose emergence is not due to the cutting of the aquifer by the topographical section, but as a result of the coating of the limestone storage massif with an impermeable sandstone or clay covering which acts as a seal and retains the water within the massif.

This is not the case with the Nabaa-el-Assal spring which is of the ordinary type, flowing when the water reaches an underlying impermeable stratum. The water infiltrating through the Cenomanian limestone of the high plateau of the Djebel Sannine percolates laterally on reaching the green clays of the Albian and breaks out along a line of contact where there is a slight bend in the beds. The mechanism of its retention in the aquifer is not the same as for the overflow springs and exhaustion is more rapid, as is indicated by the cross-section and characteristic curves of this spring given opposite. Here, the co-efficient of exhaustion is almost double that of the overflow springs considered:

$$q = \frac{2}{(1 + 0.013\,t)^2}, \text{ in cu. m./s.}$$

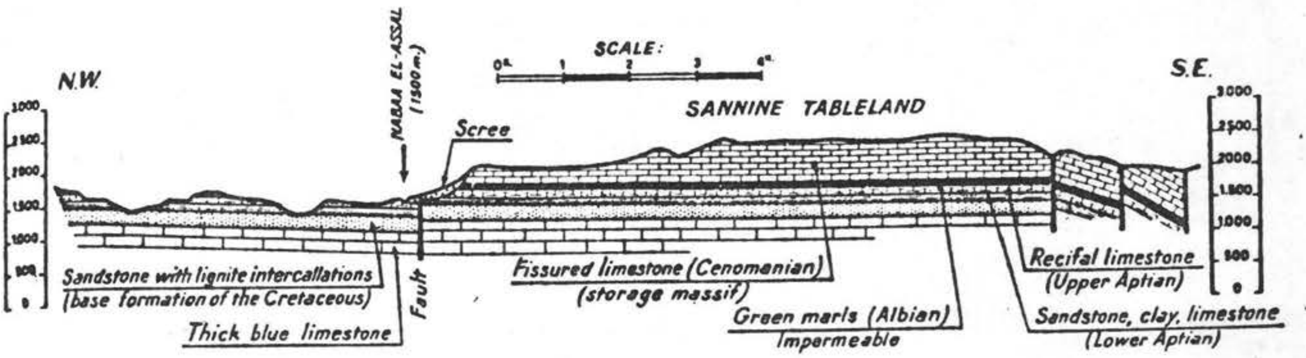
$$V = \frac{13{,}286{,}000}{1 + 0.013\,t}, \text{ in cu. m.}$$

THE RIVERS OF THE LIMESTONE FORMATIONS

There are, however, exceptions to this unusually simple hydrological picture. While the structure of the country is simple in its main lines, it is also spectacularly accidented, presenting the unusual combination of intricacy and large scale.

Thus we find that immensely powerful springs, few in number admittedly, but handling the water of a whole massif of great extent, and with their discharge practically unaffected by seasonal and even annual

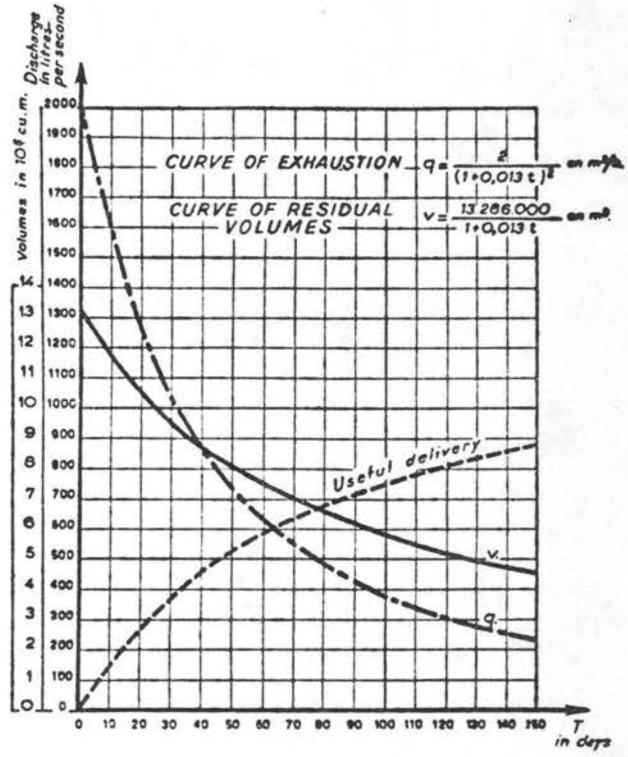
Geological section showing the hydrological mechanism of the Nabaa-el-Assal Spring



variations in consequence of the immensity of their reserves. This fact in itself is an indication of the degree to which the interior of the formation has been hollowed out by karstic erosion. Instead of a relatively stagnant water-table, we have underground rivers, deep abysses into which the water plunges, and vertical pits and sub-horizontal galleries through which the afflux of the tropical rains rushes violently. As a result of all these types of erosion within the limestone of the massifs, the water is in continual circulation, thus intensifying karstic erosion until immense networks have been developed with a maze of conduits, feeding springs of enormous volume which are full-grown rivers from the start. An example is the great Ain-Zarka source of the Orontes.

The Cenomanian slopes of the Lebanon and Anti-Lebanon ranges plunge beneath the Bekaa plain to form a vast syncline in which water from the eastern slopes of the Lebanon and the western slopes of the Anti-Lebanon ranges accumulates. The resurgence is prevented by Albian marls rising towards the surface and the evidence suggests saturation of the base of the syncline and overflow of subsequent infiltrations from low-level outlets. Discharge is of surprising regularity and the Orontes is already a river where it leaves the Ain-Zarka springs.

In an average year the discharge is between 17 and 14 cu. m. per second, minimum discharge being in the period November-December and maximum in June-July. However, the discharge remains constant within these limits even when there are wide variations in rainfall, and a year of quite exceptional drought is needed before the figure falls appreciably. Indeed a succession of dry years is required to make any serious inroads on the quantities stored, like 1932 and 1933 in which the rainfall was respectively 50 and 30 per cent below average. After such a succession of dry years the diminution of the reserves reduces the flow of the spring to 8 cu. m. per second. Being recharged by the drainage from vast surface areas and fed from deep-lying reserves, the spring is very little affected by seasonal and even annual variations, the implication



being that the supplies available from the resurgences are only a minute fraction of the reserves accumulated in the storage massifs.

The curve of exhaustion is a nearly horizontal straight line, its equation being

$$q = 17\ (1-0.001t) \text{ in cu. m.}$$

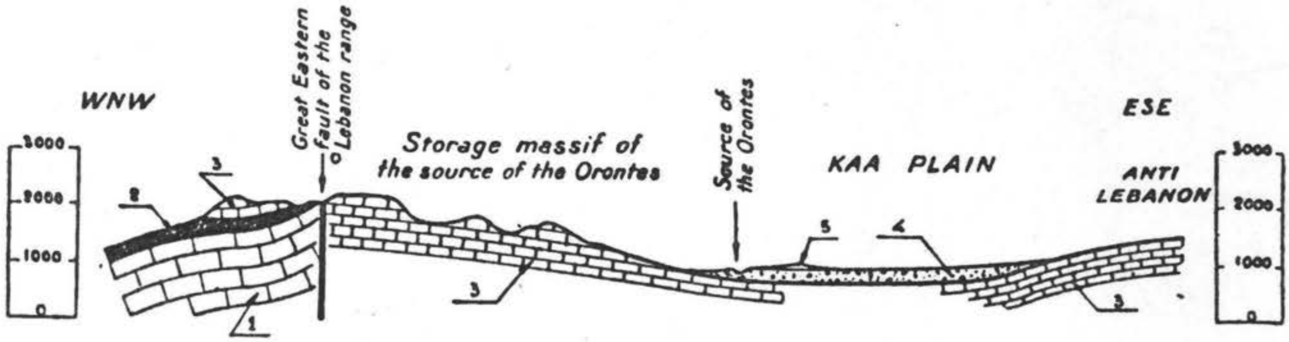
The curve of the residual volumes is a very slightly curving parabola of vertical axis representing the equation

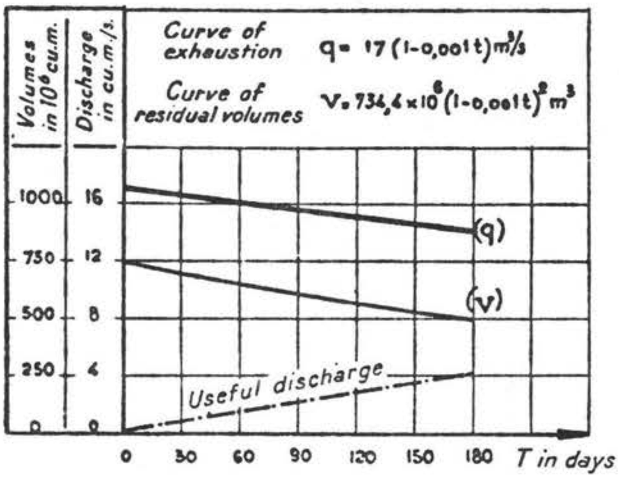
$$V = 734.4 \times 10^6\ (1-0.001t)^2 \text{ in cu. m.}$$

The useful volume for compensation of subsidence is in the neighbourhood of 734 million cu. m.

The probable area of the catchment zone of the

Geological section showing the hydrological mechanism of the source of the Orontes (minimum discharge: 8 cu.m. /s.)





1. Jurassic fissured limestone.
2. Lower Cretaceous.
3. Cenomanian fissured limestone (storage massif).
4. Pliocene conglomerate.
5. Basalt.

source of the Orontes can be reckoned at 800 sq. km. on the eastern face of the Lebanon massif with 1,000 mm. of rain and 1,000 sq. km. on the western face on the Anti-Lebanon with a rainfall of 500 mm.

Along its course the Orontes is augmented by the water of a number of major springs fed, like the Ain-Zarka spring, by Cenomanian massifs and breaking out under similar conditions. An example is to be found in the Tel Ayoun springs rising downstream from Cheizar and apparently fed by a Cenomanian area of 600 sq. km. stretching from Massiaf to the southern border of the Djebel-Zawiyé, with a rainfall of 650 mm.

The curve of exhaustion is a straight line represented by the equation

$$q = 5.3\,(1 - 0.001t) \text{ in cu. m.}$$

The curve of residual volumes is a parabola of vertical axis and of the same degree of curve as that of Ain-Zarka.

$$V = 229 \times 10^6\,(1 - 0.001t)^2 \text{ in cu. m.}$$

The co-efficient of exhaustion is the same as for Ain-Zarka and the effective supply compensating subsidence is in this instance 229 million cu. m.

The probability is that a proportion of the water feeding the Tel Ayoun springs comes from the Jurassic eastern slope of the Djebel Ansarieh (Djebel Gibli); it would be perfectly possible for this water to reach the spring via the great eastern fault under the Quaternary alluvia of the Ghab marshes.

Along a line roughly east to west, passing via the Orontes to the right of Tel Ayoun, there are the important springs of the Nahr Sène, a small coastal river 6 km. long to the north of Banias, on the western slope of the Djebel Ansarieh. In this instance too the Nahr Sène emerges as a fully-fledged river from its source, with a flow of 14 cu. m. per second.

The whole high-lying part of the Djebel Ansarieh Massif, reaching a maximum of 1,500 m. consists of Jurassic fissured limestones. The western face is Cenomanian with a few beds of green marl at the base. The water from the high Jurassic massif percolates under the Cretaceous covering and thus joins the water from the Cenomanian of the western face. The formation is ascendant in the region of the spring and rises to the surface by a system of fractures discovered to the north-east of the springs.

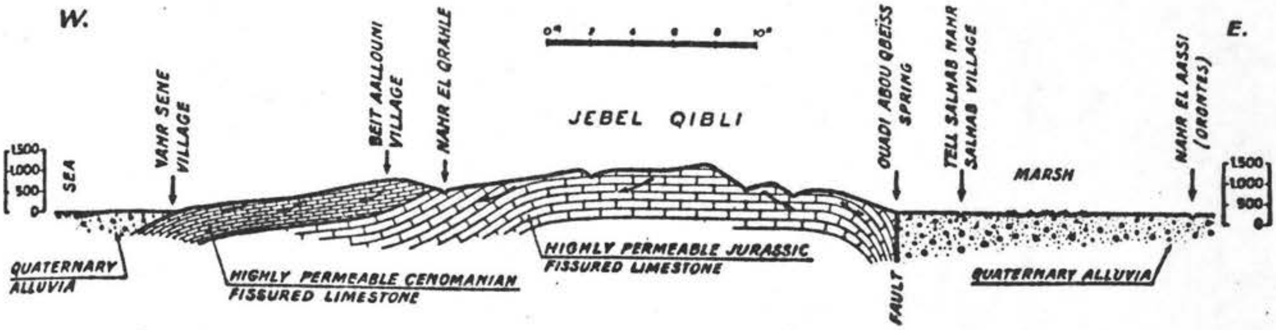
The characteristic curves are the following:

$$q = \frac{14.5}{(1 + 0.0017\,t)^2}, \text{ n cu. m./s.}$$

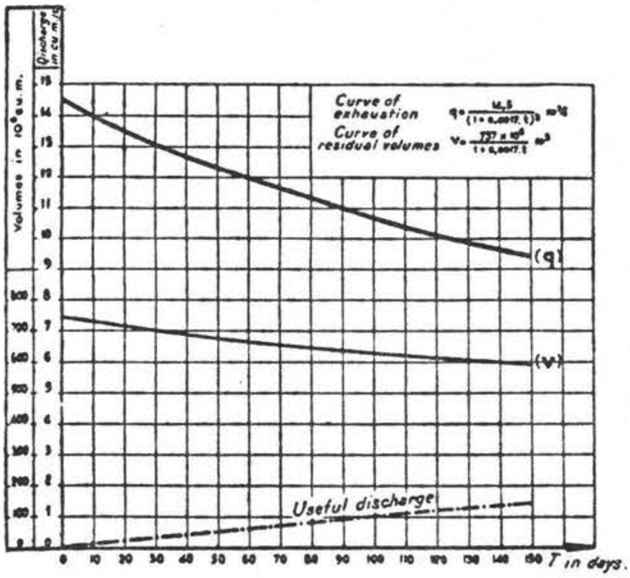
$$V = \frac{737 \times 10^6}{1 + 0.0017\,t}, \text{ in cu. m.}$$

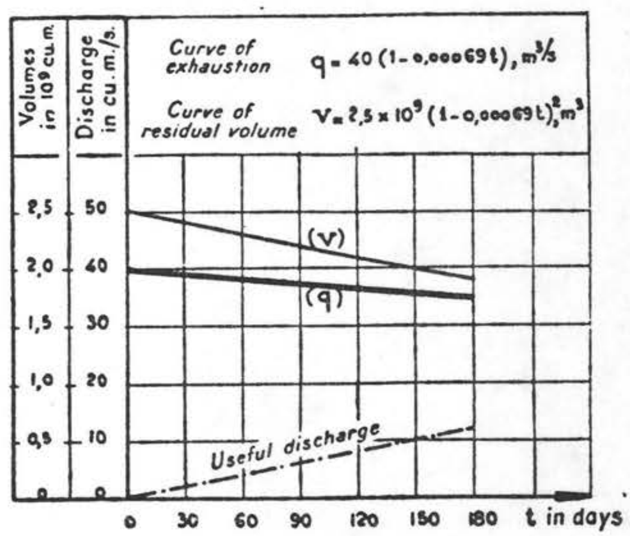
The effective volume for the compensation of subsidence is 737 million cu. m. and the total catchment area appears to be 700 sq. km. in extent, of which 600 sq. km. have a rainfall of 1,300 mm. and 100 sq. km. a rainfall of 900 mm.

The conclusion suggested by the foregoing is that,



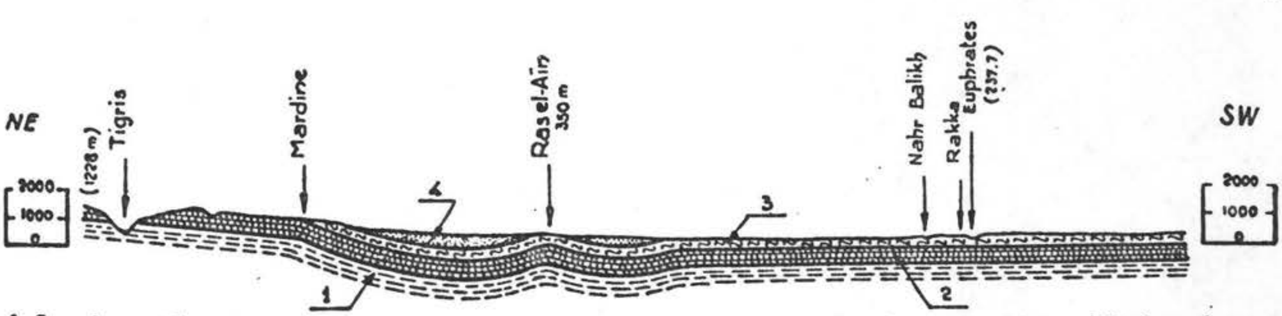
Geological section showing the recharge mechanism of the Nahr Sène Springs





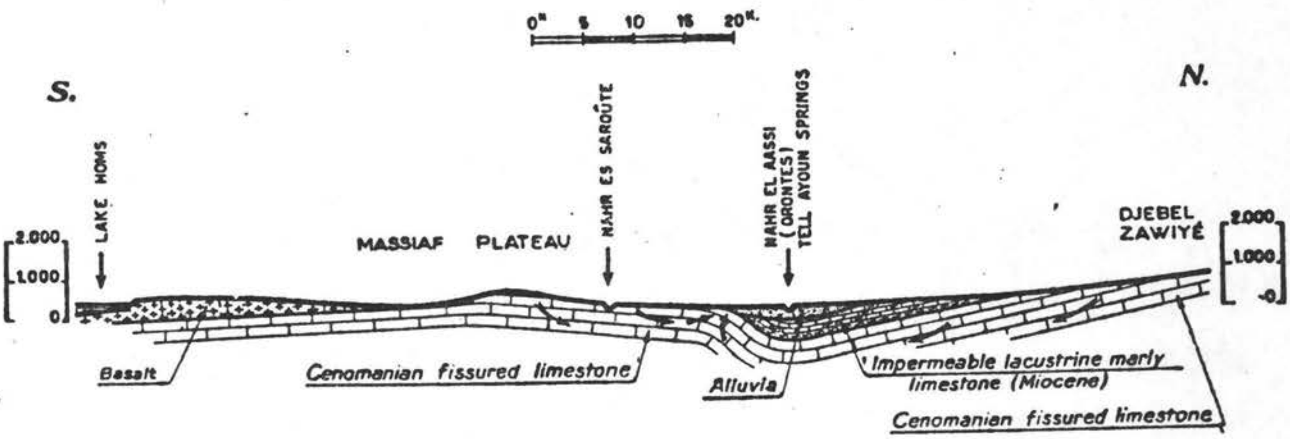
Geological section to illustrate the hydrology of the Res-el-Aïn artesian spring (minimum discharge: 40 cu.m. /s.)

Scales { Surface: 1/2,000,000
Altitude: 1/200,000



1. Senonian marl.
2. Eocene fissured limestone of high absorptive capacity.
3. Compact benches of gypsum with intercallations of porous limestone. Burdigalian-Vindobonian (Miocene).
4. Alluvia, screo, silt. Quaternary.

Geological section showing the hydrological mechanism of the Tell Ayoun springs



while the hydrology of each region exhibits individual features depending on the structure of the subsoil all these individual systems are coeval and at the same stage of maturity. The most clearly defined of them is that of the Ras-el-Ain spring, source of the Khabour, a Syrian tributary of the Euphrates. This spring emerges as a series of large spring-fed pools in the middle of the Mesopotamian steppe at a point along the boundary of the Taurus mid-way between the Tigris and the Euphrates, and is supplied by the infiltrations into the limestones of the Taurus foothills.

The eocene limestones of the Mardine area are highly absorptive of surface run-off and of high water-storing capacity when the structure is concordant, mainly horizontal and without dislocation. The Ras-el-Ain source of the Khabour emerges as a result of a slight fold of the same strata raising them nearer the surface, resulting in the gushing of true artesian springs.

The discharge varies very little, being between 40 and 35 cu. m. under neutral conditions.

The curve of exhaustion is a straight line representing the equation

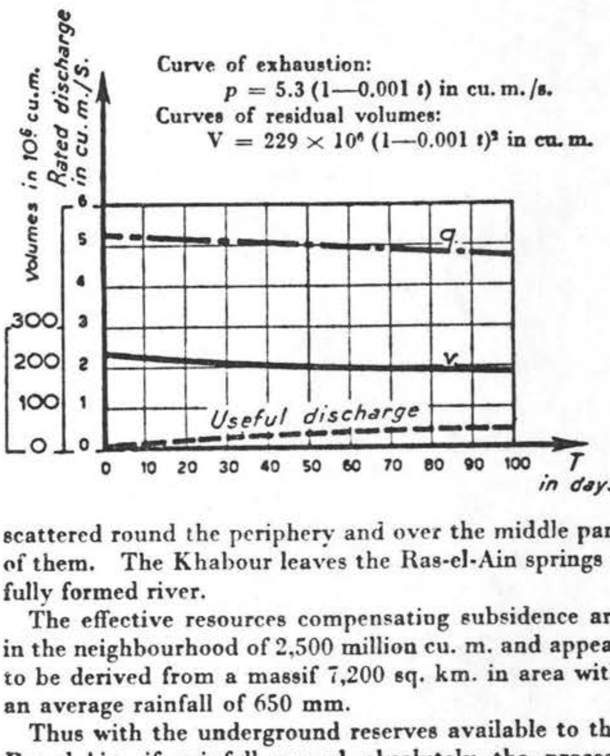
$$q = 40\,(1 - 0.00069\,t) \text{ in cu. m./s.}$$

and the curve of residual volumes is a parabola of vertical axis of even lower degree of curve than that of the Ain-Zarba source of the Orontes; its equation is

$$V = 2.5 \times 10^9\,(1 - 0.00069\,t)^2 \text{ in cu. m.}$$

With its modula of 40 cu. m. the Ras-el-Ain source of the Khabour is, as Pardé has said of it, the "queen of known springs", the strongest known limestone spring, according to him, being the Stella spring in the Frioul, Italy with a discharge of 36.6 cu. m.

Ras-el-Ain would hold the world record if it emerged from a single mouth. However the waters rise in vast spring-fed pools through a number of openings



scattered round the periphery and over the middle part of them. The Khabour leaves the Ras-el-Ain springs a fully formed river.

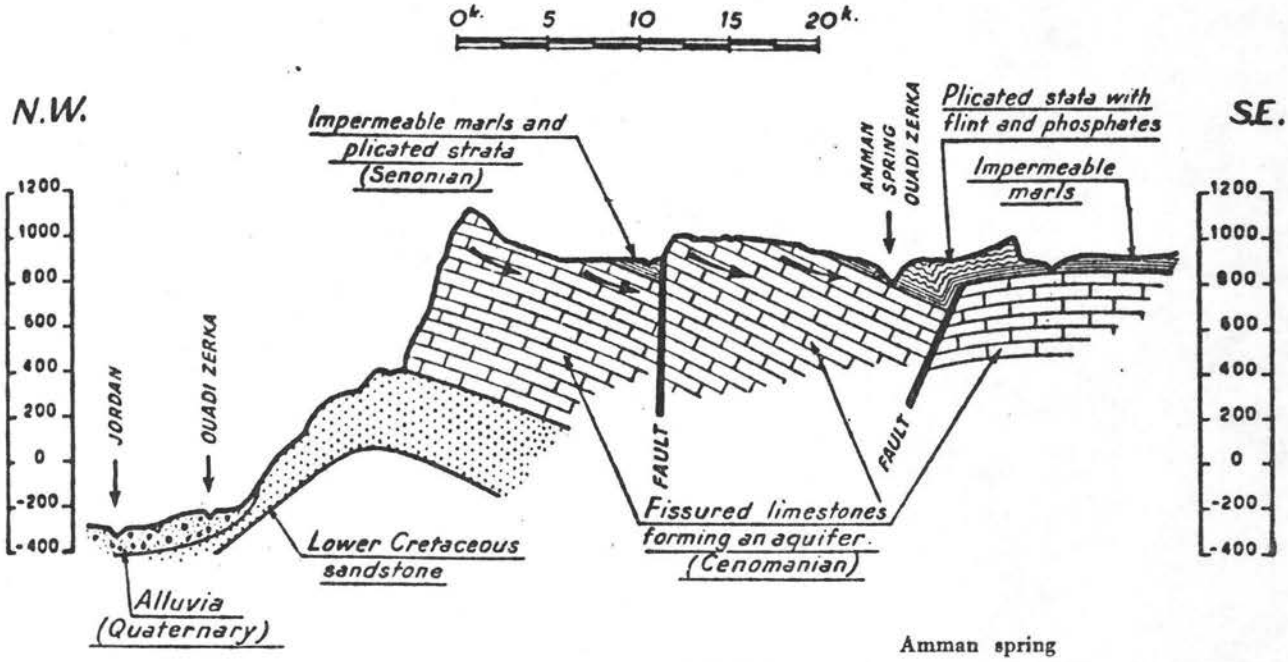
The effective resources compensating subsidence are in the neighbourhood of 2,500 million cu. m. and appear to be derived from a massif 7,200 sq. km. in area with an average rainfall of 650 mm.

Thus with the underground reserves available to the Ras-el-Ain, if rainfall ceased absolutely the process of subsidence would continue for four years before the water would be entirely exhausted and the springs dried up.

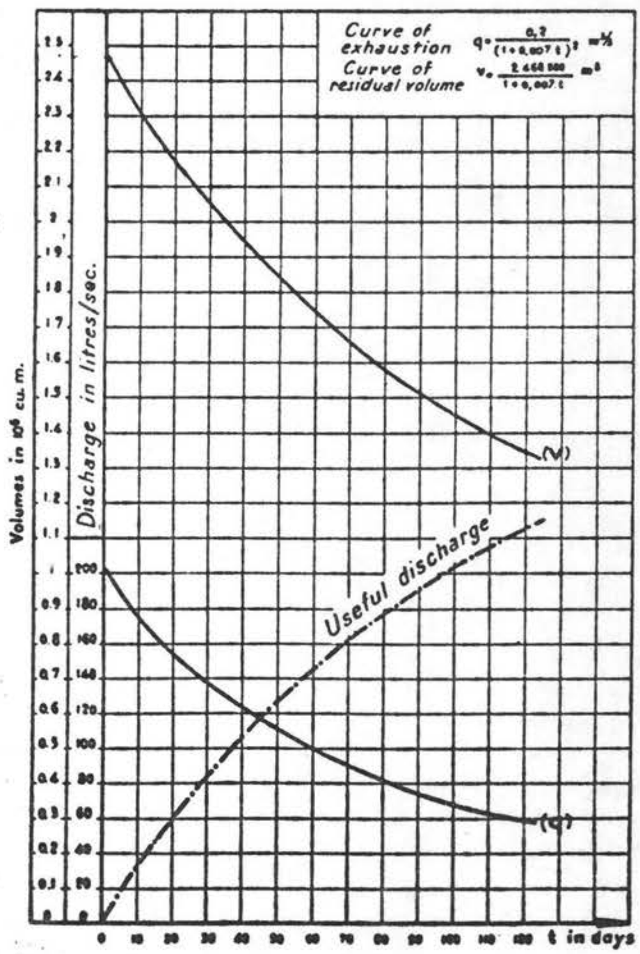
Their karstic hydrology has a highly beneficial influence in the countries of the Middle East and is the reason that conditions are not more desert-like; even in zones of extreme aridity it makes human settlement possible.

On the borders of the desert, a hydrological balance subsists which is astonishing, having regard to the climate: the explanation lies in the karstic hydrology and the wide distribution and great thickness of the limestone formations.

Geological section showing the recharge mechanism of the Amman spring



Amman spring



The springs supplying water to Amman, now the capital of the Hashemite Kingdom of Jordan, are a typical example of this.

The site of the town was determined by the presence of considerable springs rising at the point of convergence of a number of valleys. The chief spring, the Ras-el-Ain, is perennial, though in summer the table-lands adjacent to the town attain the aridity of the desert. The index of aridity is, indeed, as low as 4.5 in the Amman region.

The Ras-el-Ain and Ain Ghazel springs near the town and the more distant springs of Er-Russeifa, Zerka, and Es-Sukhné are similar in nature and mark the periphery of a great limestone vault occurring in the Djebel Es-Salt.

The geological cross-section brings out clearly the happy effects of the evolution of the limestone forming the sub-stratum of the Amman zone. This massif has a mean annual rainfall of 500 mm., whereas that of the town itself is no more than 320.

The characteristic curves of the Amman spring are:

$$q = \frac{0.2}{(1 + 0.007\,t)^2}, \text{ in cu. m./s.}$$

$$V = \frac{2{,}468{,}500}{1 + 0.007\,t}, \text{ in cu. m.}$$

and show that the usable discharge is around 2.5 million cu. m.

The cross-section also shows that the thickness of the limestone above the spring is about 200 m. There can be no doubt that the limestone below the spring's level is full of water and that it would be advantageous to lower the points of discharge to increase the flow.

The catchment area is about 100 sq. km. in extent and the massif can absorb water reserves of the order of 25 million cu. m., taking a co-efficient of 50 per cent as allowance for losses by run-off and evaporation.

CONCLUSION

The countries of the Middle East exhibit a range of climates varying on occasion to the point of being completely opposite. The relief fits the climate and from that point of view presents a picture remarkable for its simplicity.

The mountain chains play two contradictory parts; they act as climatic barriers on the coast, their mass forming a screen to block the penetration of moist air into the interior, while simultaneously they act as storage reservoirs preventing evaporation in the hinterand. On this dual hydrological mechanism the whole of the countries' living conditions depend. The extreme permeability of the strata is a prime factor in the life of the streams. Parts of the Lebanon are the highest ground (3,088 m. at Qornet-es-Saouda) between the Taurus and Zagros and between Armenia and the Yemen and Ethiopia. This vast area intercepts the bulk of the moisture derived from the sea so that aridity appears immediately inland of the coastal mountain chain. By force of circumstances rather than the favour of nature these great masses subjected to a climate of extremes and to violent downpours have evolved an original hydrological régime without which the country would be still more parched and inhuman. The pleasant contrast which the Mediterranean coastal belt presents to the hinterland is due to the special nature of water circulation in the limestone massifs.

Overall, the relief exercises a moderating influence as a result of the storage of water in abundant quantities.