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A HYDROGEOLOGICAL STUDY IN THE BASIN OF THE GULP CREEK – A RECONNAISSANCE IN A SMALL CATCHMENT AREA

1. Groundwater flow characteristics

(with an abstract in English and in French)

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Abstract

The results of a hydrogeological reconnaissance in a small catchment area are discussed. The study is mainly concerned with the relationship between the regional environmental conditions such as geological framework and composition, topographic relief, climate and the groundwater regime.

It is shown that the geological history has been of vital importance in determining the surface and groundwater flow. Discharge hydrographs are presented and their hydrogeological significance is discussed. The hydraulic continuity between the lithostratigraphic members is emphasized and the occurrence of zones of preferential groundwater discharge is indicated. The localization of karst features, its relation to tectonic deformation and its influence on the groundwater regime is demonstrated.

Résumé

Les résultats d'une exploration hydrogéologique dans la partie sud du bassin de la Gulpe – située dans la région frontière belge-néerlandaise – y sont discutés. La recherche est portée sur une relation mutuelle entre la situation géologique, lithologie et relief topographique compris, et entre la manière dont se présentent les eaux superficielles et les eaux souterraines.

L'importance de l'histoire géologique du bassin en rapport avec le mouvement de l'eau et la nature de la présence de l'eau superficielle et de l'eau souterraine y est accentuée. Les hydrogrammes des eaux superficielles et leur signification hydrogéologique y sont discutés. La continuité hydraulique entre les différentes unités lithologiques y est accentuée et la présence des zones préférentielles pour les parcours des eaux souterraines y est énoncée.

La présence et la localisation de phénomènes karstiques sont discutées, tandis que leur grande influence sur la circulation et les écoulements des eaux souterraines est commentée.

1. Introduction

For the past four years hydrogeological field studies have been undertaken in the valley of the Gulp creek – a tributary of the river Geul in the S.E. part of the Netherlands. These studies are carried out during the spring and summer seasons by small groups of students from the Agricultural University in Wageningen (The Netherlands) under the direction of the authors.

The primary purpose of this catchment study is to present an adequate training project in which a variety of hydrogeological problems can be studied. The project is planned to continue over a period of about 7 years.

The hydrology of a drainage basin may be viewed as a system maintained by a throughput of water in which the surface and subsurface water regimes form a sequential dynamic unity. The behaviour of the system is dependent on the geological framework of the basin; in other words, the interrelationship between input, storage and output elements of the system is largely controlled by the basin geology. In order to evaluate the hydrogeological environment of the Gulp Basin, the stratigraphy, structure and surface extent of the various lithological units have been mapped, paying particular attention to their water bearing properties. Vertical water level float recorders have been installed at selected sites to provide continuous records of surface water discharges and groundwater fluctuations. Surface water and groundwater are sampled for chemical analysis at standard locations every month and every second month respectively. Precipitation is measured with the aid of a pluviograph and samples for analysis are regularly taken.

For chemical analysis of the water the concentrations of Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, HCO_3^-, CO_3^{2-}, Cl^-, SO_4^{2-} and NO_3^- were determined. Non-ionized silica (H_4SiO_4), the pH and the specific conductance were also determined. Inasmuch as the cation and anion totals were found to be equal or approximately equal, the analysis was considered to be sufficiently comprehensive. The water analyses were carried out at the chemistry laboratory of the Soil Survey and Geology Department of the Agricultural University of Wageningen. The pH and specific conductance were also measured in the field. Special precautions were taken when collecting the water samples for chemical analysis, details of which will be given in a separate paper dealing with the hydrochemistry of the Gulp Basin.

In this report the evaluation of the hydrogeological environment is related to the movement of groundwater and surface water, and not to its economic use for water supply purposes.

2. Location, topography and climate

The basin of the Gulp Creek begins just north of Henri-Chapelle in Belgium, crosses the Belgian-Dutch border near the small village of Slenaken and continues in a northern direction up to the village of Gulpen where it joins as a tributary the river Geul; the river Geul in its turn debouches into the Meuse farther to the northwest (cf. fig. 1).

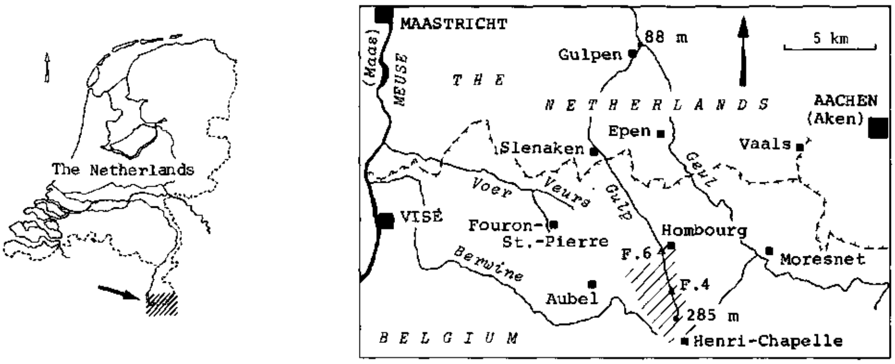


FIG. 1. Location of the study area; F4 and F6 are stream gauging stations.

The total length of the valley is approximately 18 km, the maximum width between the topographic divides about 4 km while the total surface area of the basin is about 4,600 ha. The perennial stream starts at an elevation of approximately 285 metres + O.P. (O.P. = Ostende Peil) and joins the Geul at 88 m + NAP (OP ≈ NAP). The average discharge for the Gulp Creek where it joins the river Geul amounts to approximately 350 litres per sec. The stream is of a misfit type, in the sense that it is too small for the valley that it occupies. It is supposed that the underfit condition is a legacy of the Pleistocene time, when permafrost conditions prevented percolation underground. During periods of thaw, confined to the surficial layers, hillslope processes and peak discharges would cause strong erosion and valleys were actively widened and deepened. Carbon 14 measurements of groundwaters seem to favour the above supposition. Carbon 14 data from Central European groundwaters (GEYH, 1972) indicate that none of the investigated groundwaters have ^{14}C ages between 13,000 and 20,000 years. Permafrost conditions during Late-Glacial time rendered the near surface layers impermeable and thus effectively prevented groundwater recharge.

The medium size of the basin is convenient as it is not too big for an adequate measurement of precipitation and discharge, not too small on the other hand that trifling local variations in bottom conditions would strongly affect the various measurements. The primary purpose of this catchment study being is to act as a training facility makes the size of the basin an important factor in that the overall-picture remains visible, especially during fieldwork.

The southernmost part of the basin was selected to start with a reconnaissance survey. The aim was to find out the major hydrogeological characteristics and to apply the results obtained in the other parts of the drainage basin. The area comprises the upper reaches of the basin and measures a total surface area of about 730 ha. Most of the instrumentation has been installed in this area and also most of the field surveys have been carried out there. Hence, the present report is based mainly on observations here; it is clear, however, that surveys in adjacent areas had to be carried out as well.

The catchment begins as a dry valley at about 357 metres + O.P. and carries surface water from around 285 metres + O.P. where groundwater discharges slowly over some area rather than from a definite localized source. Schematically the area is depicted in fig. 1. The stream gauging station F6 measures the total discharge of the study area; F4 is another stream gauge, at about the midpoint of the area.

Of the total 730 ha, about 50 ha are forested, 20 ha are arable land (mainly corn crops); the remainder is pasture. The dwellings are not concentrated; there are about 35 farmhouses and some 15 private houses, approximating some 4.5 ha in area. There is about 5 ha paved road.

The cross profile of a valley is often asymmetrical; this is also true for the Gulp valley. The steepness of the eastern valley slope amounts to about 17% (9.5°), while the more gentle western slope averages 5% (3°). Consequently 200 ha of the catchment lie at the eastern side of the Gulp Creek, while some 530 ha cover the western valley side. There seems no obvious lithological or structural cause for the asymmetry, but periglacial processes and simultaneous regional uplift may have contributed to a lateral shifting of the stream from west to east.

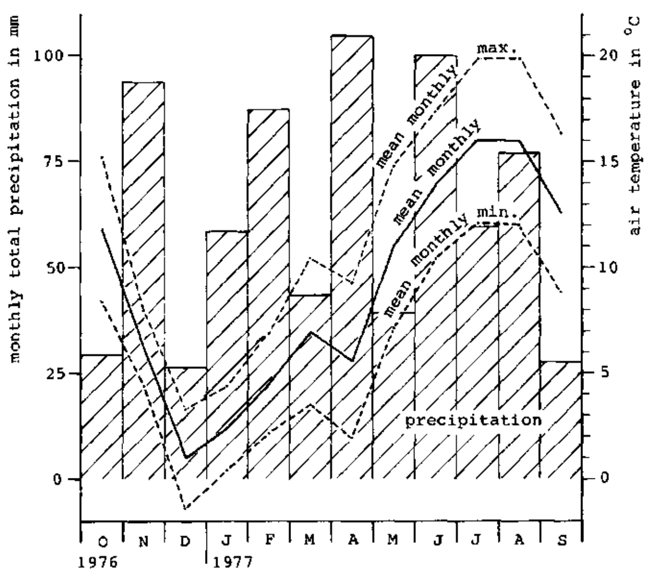


FIG. 2. Monthly total precipitation and air temperature data from the hydrogeologic field station at Hombourg (Austen).

The climatological conditions in the region of the Gulp basin can be described as humid temperate; according to Köppen's classification as a temperate rainy (humid mesothermal) climate, moist in all seasons. The average annual precipitation amounts to 890 mm. The period of drought in 1975 and 1976 is accentuated by a precipitation of 606 and 535 mm respectively, measured with the recording rain gauge in Hombourg.

Rainfall intensity is highest during the summer months. Intensities higher than 10 mm per hour were recorded 3 times between May 1974 and January 1978. The highest rainfall intensity measured was 19.5 mm per hour during a thundery storm. Precipitation intensities during the winter months are lower and average between 1 and 3 mm per hour.

Published data from the Royal Meteorological Institute at Ukkel, Belgium (Weather Bureau Bierset, at about 34 km S.W. of Hombourg, 175 m + OP), give annual evaporation rates for open water surfaces of 650 mm as an average for the period 1970-1974 and 674 mm for 1975. Temperature recordings at the field station in Hombourg for the period between October 1976 and September 1977 show that December and June have been the months of lowest (–11 °C) and highest (29 °C) temperature respectively. Maximum temperatures above 20 °C were measured only between May and September, whereas temperatures below –5 °C have been recorded between December and April (cf. fig. 2).

3. The geological framework

a. *The Gulp Basin and surroundings.*

The area of investigation (cf. figure 3 and table 1) is situated near the northern margin of the Ardennes upland, where the Hercynian fold belt meets the low plateaus with subhorizontal Mesozoic and Cenozoic cover; these low plateaus can be regarded as a transitional zone to the lowlands of Holland. The Ardennes uplands are plateau mountains produced by uplifting during the Late-Tertiary and the Pleistocene (cf. Rutten, 1969). The uplift has also affected the Ardennes foreland and the tilting, during the upward movements, is expressed by *a general 1-2 degree northwestern dip of the Mesozoic and Cenozoic cover.* The Hercynian structures of the Ardennes continue in a northerly direction into the subsoil of the Netherlands. The Paleozoic basement crops out in the Ardennes uplands, but is exposed in the foreland only where the valleys are deeply incised and have cut through the cover. The discordant relationship between the uplands and the plateau lowlands is also expressed in the rock types that occur in the Hercynian basement and the sedimentary cover, viz. indurated (mainly sandstones and shales) and nonindurated rock types respectively. Its hydrogeological significance is self explanatory and emphasizes what can be inferred from a glance at fig. 3, that is the basin geology is a dominant control for the gross characteristics of the stream network and its density, and that underground storage may be expected to be larger in the Gulp Basin when compared to the basins of the Berwine and Geul rivers.

Fig. 3 sketches the location of the drainage basin of the Gulp Creek in between the adjacent catchment areas of the Berwine to the west and the Geul to the east. Although the stream networks are simplified because of the scale of the map used, some marked differences in the basic patterns of the drainage systems can be recognized. The Berwine and the Geul basins show well developed drainage networks with many branches feeding the trunk streams, the Gulp Creek on the other hand shows a poorly developed system with the main stream and only a limited number of tributaries which join the main trunk at approximately right angles. Morphologically the Berwine pattern may be classified (cf. THORNBURY, 1969) as dendritic, the Geul network is more complex,

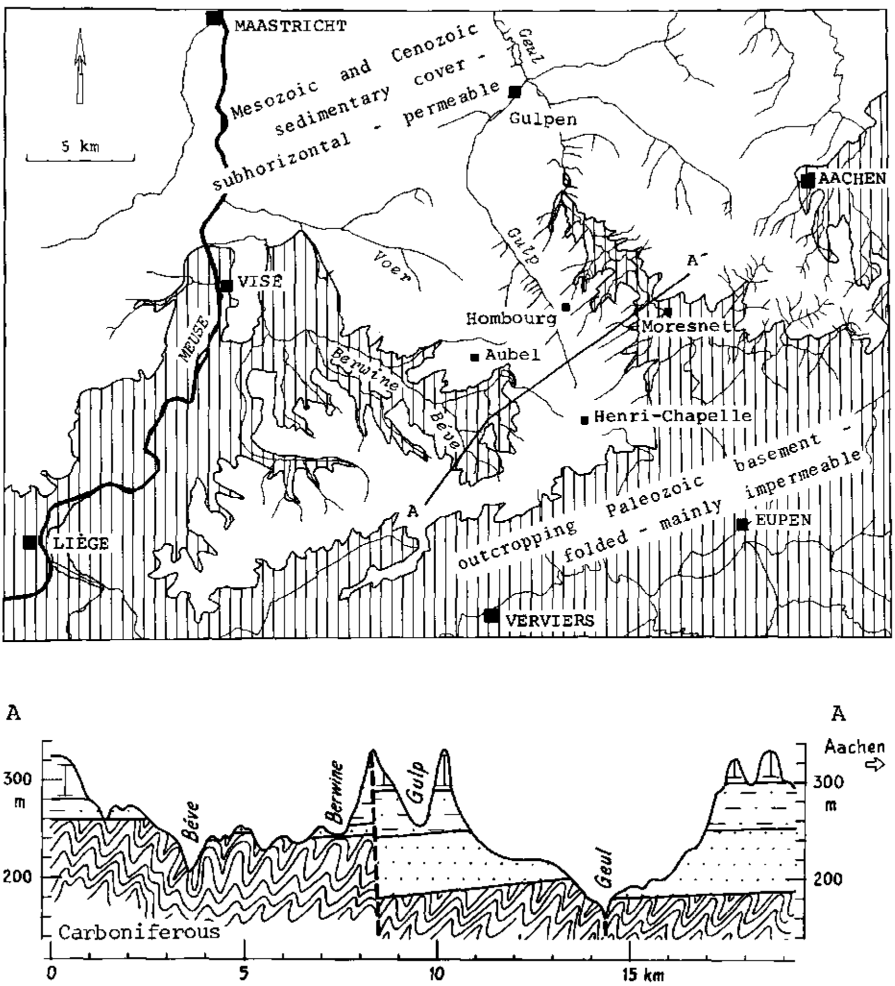


FIG. 3. Geological framework of the Gulp Basin and surroundings.
For stratigraphic legend cf. fig. 4.

with dendritic as well as trellised features, whereas the Gulp drainage net may be viewed as a modification of a trellis pattern in which the tributaries are consistently more developed on one side of the valley than on the other.

The form of a particular drainage basin is a product of its geological history in its broadest sense and the inherited shape in its turn influences the processes which operate to-day. The study of the drainage pattern evolution, however, lies beyond the scope of the present report. Such a study must include not only the influence of epirogenetic movements on the development of the drainage basins but also the manifold influences of the geologic and climatic changes during the Pleistocene as well as the effect of time. Simply, it might be suggested that the Gulp Basin, indeed, when considering the established geologic principle that drainage 'development' increases with the passage of time, is of younger age than the adjacent basins; however, the fact of the differences in lithology should make cautious comparisons advisable; especially, as the differences in lithology have originated from uneven uplift.

Altogether, the stream systems as depicted in fig. 3, and including the Voer and Veurs basins, situated to the north of the Berwine, all have their main direction of drainage to the northwest, reflecting the regional tilting. The deflection of this general direction for the lower part of the Gulp Creek just before it debouches into the Geul is obvious and is assigned to a local difference in the direction of tilting, viz. a tilting in a northeastern direction. Subsurface data from the Geological Survey at Heerlen support this view (personal communication).

b. *The catchment area of the Gulp Creek.*

The sources of information available on the basin geology were the geological maps and borehole files from the Geological Surveys of Belgium (Brussels) and the Netherlands (Heerlen) and the data obtained during our fieldwork, including resistivity soundings.

The geological conditions in the area under discussion are represented in figures 3 and 4; both the plan views and the cross-sections are simplified because of the limited data available. The cross sections indicate that *rocks of Paleozoic age underlie the basin.* The Paleozoic rocks are sedimentary, folded and as far as data are available from borings and outcrops in the adjacent area, the formations generally consist of interbedded fine grained sandstone and shale. The discordant relationship between the Paleozoic bedrock and the Mesozoic cover is expected to form a rather irregular relief with weathered shales and sandstones on top of fresh bedrock, as is also evidenced from borings. The Paleozoic bedrock is considered to form the *impermeable base of the flow system*, although at depth Carboniferous limestones occur.

The *Mesozoic formations* that cover the Paleozoic bedrock are of Upper-Cretaceous age. The Aken, Vaals and Gulpen Formations respectively, (all local lithostratigraphic names) are of marine Upper-Senonian origin (cf. table 1).

Lithologically the *Aken Formation* (Aachen Sand) consists of nonindurated sandy clays and silty clays for the lower part of the series and of light coloured

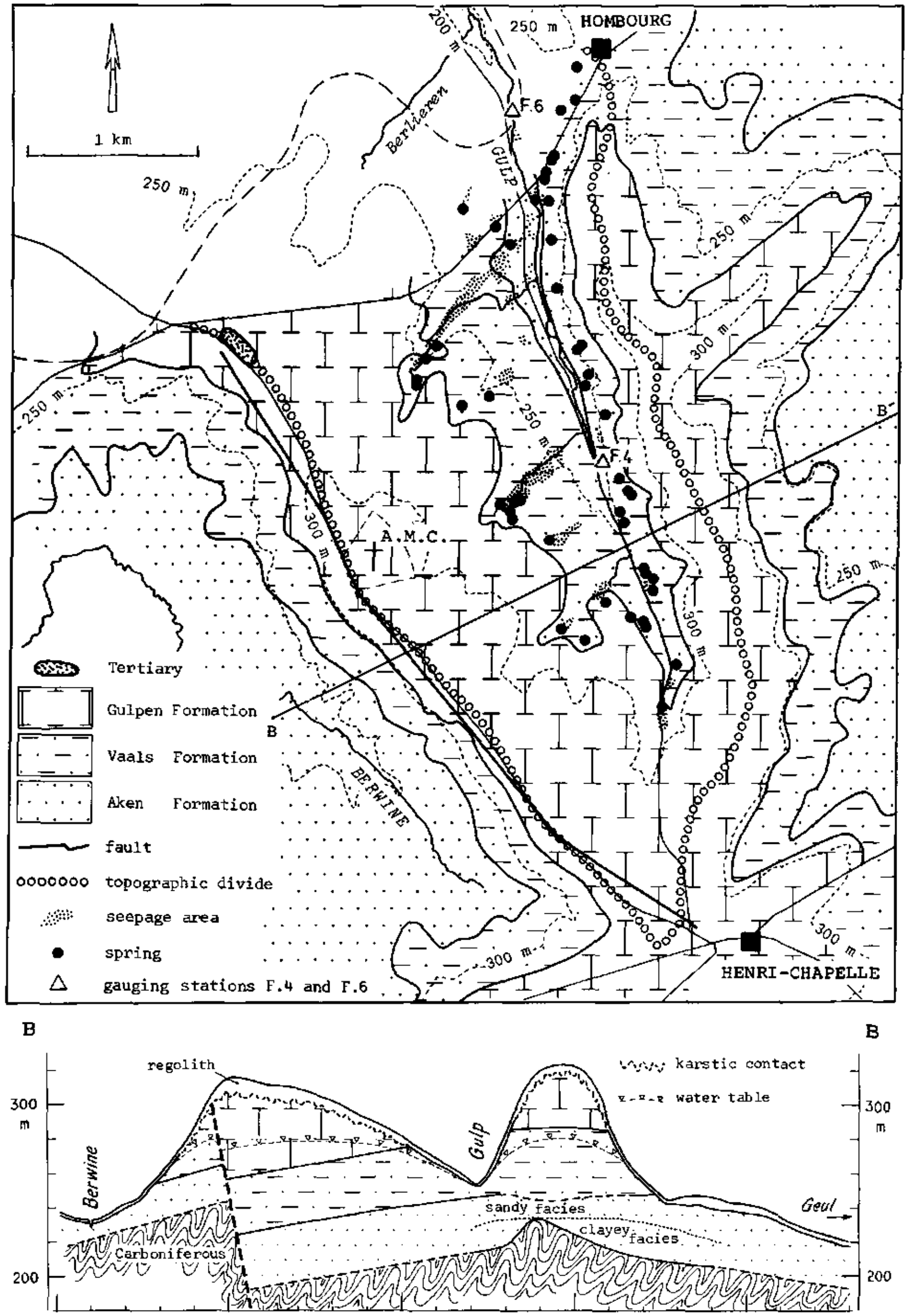


FIG. 4. Map and cross section showing the general hydrogeological conditions in the southernmost part of the Gulp Basin.

fine grained well sorted quartz sands for the upper part; the Md value for the quartz sands amounts to 150-200 microns but no grainsize data for the lower clayey part are available yet. The Aken Formation is considered to have been deposited under nearshore conditions, possibly in a tidal flat environment; the maximum thickness of the formation may amount up to about 60 metres, while the upper sandy part is 40 metres thick maximum (FELDER, 1975). According to fig. 4 it measures about 35 m altogether in the basin.

The *Vaals Formation* (Herve Greensand) lies on top of the Aken Formation. The transitional zone often is a thin (up to 10 cm) conglomerate layer with quartz, quartzite and sandstone pebbles. In the main, the Vaals Formation consists of clayey fine grained sands and silts with glauconite. According to an east to west cross-section from Aachen to Aubel (FELDER, 1975) the formation is sandy near Aachen and gradually becomes finer – more silty and clayey – westward, viz. in the drainage basin of the Gulp Creek. The numerous hand-borings carried out in the basin showed that the sequence is dominantly developed in a clayey, very fine sand and silty clay facies, indeed. Grain-size analyses from a 20 metres boring in the basin show clay contents averaging between 25-30% for the upper 12 metres and 8 to 10% for samples from between 12 and 20 metres. The occurrence of well developed thin (10-20 cm) consolidated sandstone layers and concretions particularly in the deeper part of the boring (12-20 metres) was striking. When considering the east-west cross-section, cited above, it is most tempting to correlate these sandstone beds with either one of the characteristic horizons of the formation, e.g. 'the Horizont of Grenspaal 7' or 'the Horizont of Beusdal'. However, a further lithological study will be necessary to arrive at a definite conclusion.

In general, the available regional data (cf. FELDER, 1975) indicate that (1) the lateral facies changes in the Vaals Formation are significant; (2) in the area of study the upper and lower part are developed predominantly in a clayey (silty) facies, while the middle part shows intercalations of sandy layers, which are consolidated and thin bedded at some levels; and (3) in the basin the thickness of the formation amounts to nearly 40 metres (cf. fig. 4). It is generally considered that the Vaals Formation was deposited in a littoral, probably tidal flat environment.

Lithologically the *Gulpen Formation* stands out very clearly against the underlying formations. The formation is made up of a fine grained light coloured, friable limestone. Petrographically it should be classified as a calcilutite or rather calcipelite (cf. NOTA and LORING, 1973, BATHURST, 1975). Similar porous, lightly cemented and friable carbonate deposits are known as chalk. The transition between the Vaals Formation and the Gulpen Chalk is marked by a limestone of approximately 1 m thickness with abundant glauconite and bioturbations particularly at the base. Stratigraphically the Gulpen Formation has been subdivided into several zones (cf. table 1); in the area of study the lowermost section, named 'Limestone of Zeven Wegen' is found. The carbonate content amounts to over 80% and silifications are rare and developed only vaguely. Most of the limestone is soft and poorly bedded, but joints and fissures

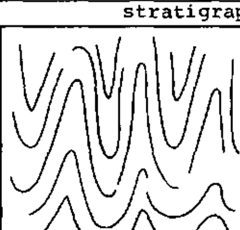
Period	Epoch	Series		subdivision (members)		layer properties	max. thickness (m)
Tertiary	Paleocene	Dano-Montian	Houthem Formation		generally unconsolidated - subhorizontal		
CRETACEOUS	UPPER SENONIAN	Maastrichtian	Maastricht Formation			yellow coarse-grained limestones with chert horizons	>80
			Gulpen Formation	Lanaye Limestone		white fine-grained limestones with chert horizons	80
				Lixhe Limestone			
				Vijlen Limestone		grayish fine-grained limestones	
				Beutenaken Limestone		white fine-grained limestones, with horizons rich in glauconite	
		Campanian		Zeven wegen Limestone			
			Vaals Formation	*grenspaal 7 sandstone*		fine-sandy, clayey silts and silty clays, rich in glauconite with interbedded fractured sandstones, a.o.	>100
		Santonian	Aken Formation	Aken Sand		white and yellow sands with cemented zones and intercalated clay layers	60
				Hergenrath Clay		mottled clays	
stratigraphic hiatus							
Carboniferous	Lower Silesian	Namurian			consolidated-*folded*	"imperveous" - shales and fine-grained sandstones	

TABLE 1. – Litho-stratigraphic data from the Gulp Basin and surroundings.

are common. At some levels, however, the bedding planes are better developed and at the same time the chalk is somewhat more cemented; bed thicknesses are usually between some 20 and 60 cm. Hardgrounds as well as layers of shale or chert have not been encountered in the outcrops, that are relatively scarce in the basin; also, the available literature does not mention it (FELDER, 1973, 1975). Altogether the Gulp Formation can be described as a soft, fairly homogeneous fine grained chalk traversed by regularly occurring joints and fissures. The joint system has not been studied in detail to date mainly because of the lack of suitable exposures. The thickness of the limestone sequence in the basin may amount to approximately 40 metres.

As a result of the regional uplift most of the *Tertiary deposits* have been removed by erosion and occur only locally, either as isolated patches in the regolith, or as a more coherent body in large solution holes developed in the underlying Gulpen Formation limestone.

At some places, Tertiary material originally overlying the limestone has filled the solution holes and thus escaped from erosion. An example of this type of occurrence is present in the northwestern part of the area as indicated on fig. 4. The section is about 10 metres thick and is composed of a series of light coloured well sorted fine grained sands (Md-values between 80 and 120 microns) of marine, probably nearshore origin; stratigraphically they are generally thought to be Oligocene in age.

The regolith overlying the various geologic formations discussed above forms a blanket of variable thickness. This residual overburden generally is less than 2 metres thick on the steeper eastern slope and is thicker on the more gentle western slope. The thickness is particularly variable, however, where it lies on top of the Gulpen Limestone, because of solution holes; thicknesses up to 10 metres have been found in borings. The composition of the regolith varies greatly from place to place; in most cases it is composed of an admixture of chert nodules, clay size material and löss. The regolith generally can be regarded as allochthonous as being replaced, most probably under periglacial conditions. However, the compositional relationship with the underlying geologic formation can be recognized in most cases.

It has been mentioned above that the limestone section in the area of study is practically free of silicifications. The abundance of chert nodules and their varied character in the regolith, on the other hand, indicates that the nodules must have originated from younger zones of the Maastrichtian, that were overlying the present section (cf. table 1). In other words, not only most of the Tertiary deposits have been removed by erosion, but also various zones of the Cretaceous limestones are lacking.

4. THE HYDROGEOLOGICAL ENVIRONMENT

The hydrogeological environment of the Gulp Basin is determined mainly by the three components geology, topography and climate. Various aspects related to each of these components have been discussed in the preceding chapters. In addition to this general picture a number of features that are particularly related to the occurrence and natural movement of groundwater, will be considered in this section.

(a) *Geology*

(1) The *regolith* is sufficiently permeable for infiltration. There are no indications that overland flow occurs in the area of study. Permanent pasture covers 90 per cent of the area. The infiltration rate is mainly determined by the surficial layers and the effect of the permanent grass vegetation on the formation of an open pore structure with relatively high permeability. The saturated vertical permeability for the upper 50 cm was found to range between approximately 0.50 and 4.00 m/day, being dependent to a large degree upon the frequency of bioturbations. These data altogether make clear (see also under climatological conditions, p. 5) that overland flow in the area will be very unusual.

(2) The *Gulpen Formation* has been described in the previous section as a fine grained fairly homogeneous chalk, traversed by regularly occurring joints and fissures. The fine-grained granular texture of the chalk gives it a good storage capacity – laboratory values from porous block samples show total porosities of approximately 35 to 40 per cent – whereas the presence of fractures and fissures with dissolution along these cracks will substantially increase specific yield and permeability, making it anisotropic, when considered on a small scale. Specific yield values from separate porous blocks range from 2 to 4 per cent, whereas a first approximation of the hydrologic balance for the watershed points to values near 10 per cent. The last figure is more credible since the fractured chalk consists not only of porous blocks but of both blocks and their adjoining fissures, which results in a pressure differential and the subsequent flow exchange between porous blocks and fissures. (cf. BOULTON and STRELTSOVA, 1977.)

The dissected relief that has developed as a result of the regional uplift since the Late-Tertiary, has contributed to faster groundwater circulation and thus made the environment favourable for the solution of carbonate rocks. Because of the particular character of the chalk the solution cavities will be smaller compared to those which are typical of the indurated and massive (Carboniferous) limestones; however, the interconnectivity can be expected to be high as a result of secondary porosity of the rock. The friable structure of the chalk makes the rock incompetent to support roofs of large underground caverns. Therefore, in chalks channelization of groundwater flow into a well developed and integrated system of conduit caves seldom occurs; instead, as long as solution is limited to enlargement of existing fractures, the hydraulic conductivity will be in general uniformly distributed throughout the rock and the groundwater movement will be mainly of the diffuse flow type (cf WHITE, 1977).

(3) The *boundary between the Gulpen Formation and the underlying Vaals Formation* is marked by a band of springs, seepages and boggy soils. The Vaals

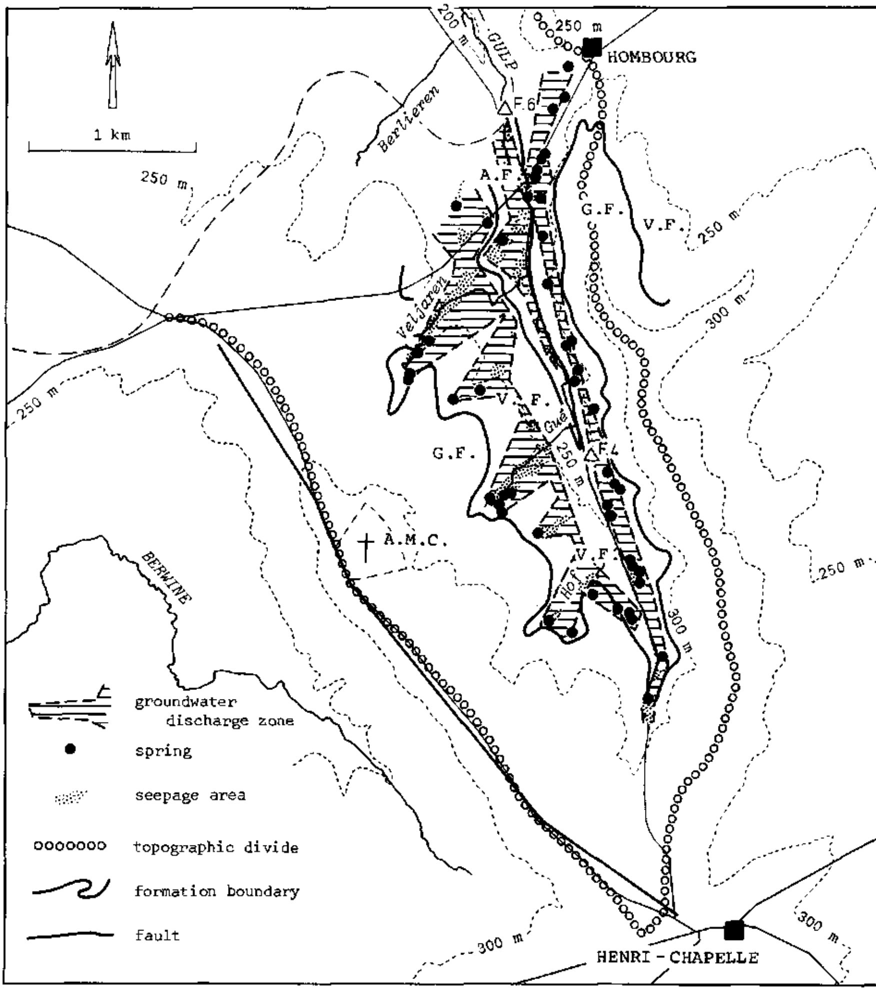


FIG. 5. Simplified map showing groundwater discharge zones in the study area. G.F. = Gulpen Formation; V.F. = Vaals Formation; A.F. = Aken Formation.

Formation consists of silty clays and intercalated clayey fine grained sands and silts with glauconite (see previous section). In the main, the Vaals Formation has to be regarded as a unit of lower permeability. Accordingly, the permeability contrast near the Gulpen-Vaals contact is developed as *an area of groundwater discharge*. The general distribution of springs and seepages is shown in fig. 5. There is a reasonable correlation between the upper boundary of the discharge zone and the Gulpen-Vaals contact along the western valley flank; the pronounced erosional surface incisions in the tributary valleys give rise to the zig-zag course of the border line. The lower border line of the discharge zone along the western valley flank appears not to be connected with the Gulpen-

Vaals contact: instead it is defined by a number of springs and diffuse discharges that issue from consolidated sandstone layers within the Vaals Formation.

Outcrops have revealed that the *consolidated sandstones are fractured* – probably as a result of uplift and tilting – and that groundwater emerges from the fractures. In the study area these sandstone beds occur at a level of some 25 metres below the Gulpen-Vaals contact. Within the layered Vaals Formation the fractured sandstones, intercalated between low permeable silty clays, act as the zones of higher permeability. The unconsolidated silty clays and clayey fine sands are not considered as confining beds in the sense that they form an absolute barrier to water movement; instead it is assumed that there is *hydraulic continuity*, which is very likely for the *sedimentary facies of the Vaals Formation*, i.c. the overall depositional pattern of tidal flats with lenticular and irregular shaped sediment bodies, deposited by shifting currents. In this layered sequence the fractured sandstone beds are considered to drain the adjoining layers of lower permeability and thus behave as *preferential zones of groundwater flow.*

Along the steeper eastern valley flank the zone of groundwater discharge is pressed together in a relatively narrow strip. The localization of springs and diffuse discharge has appeared to be connected only to the level of the fractured sandstones of the Vaals Formation; no groundwater discharge has been observed near the Gulpen-Vaals contact. This is in accordance with the observation that during the period of study the groundwater level across the eastern valley flank was always found below the Gulpen-Vaals contact. It is obvious

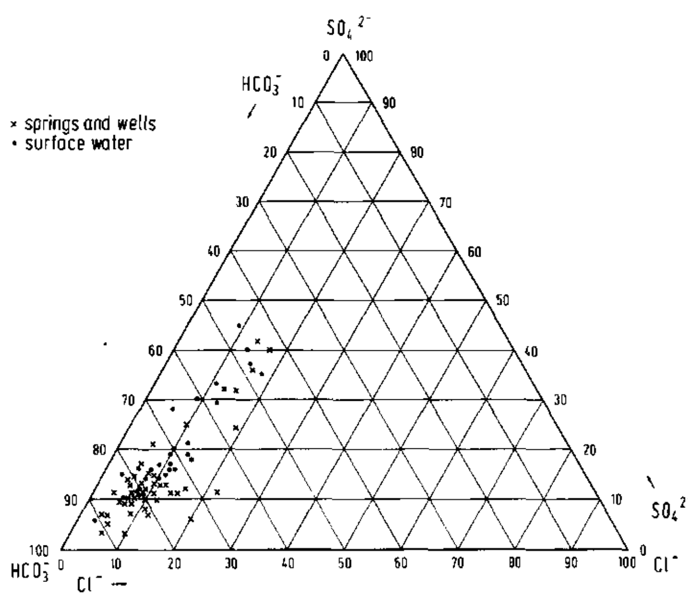


FIG. 6. Trilinear diagram illustrating hydrochemical relationship between surface water and groundwater in the study area.

that the greater slope of the eastern valley flank results in an increased lateral groundwater flow towards the valley bottom; in other words the greater hydraulic gradient along the steeper eastern flank induces a faster drainage when compared to the more gentle western valley flank (cf. fig. 4).

Altogether over 50 springs have been mapped in the area. The majority of these springs have a discharge lower than 1 l/sec.; only two have a discharge higher than $2^1/_2$ l/sec. The spring with the largest discharge was found in the northeastern corner of the study area with a maximum flow of nearly 8 l/sec. The various springs show measurable fluctuations in discharge as well as in their chemistry in response to seasonal differences in precipitation.

Some general information on the hydrochemistry in the catchment is given in fig. 6. Although groundwater and surface water show the usual differences in the total amount of dissolved solids (approximately 7 and 6 meq/l respectively) the compositional relationship is very clear. Generally, the water is of the calcium-bicarbonate type. Differences for samples from wells and springs are related to the geological formations, viz. samples from the Vaals Formation contain some sulfate, that most probably is derived from pyrite, that was identified in thin sections, indeed. Further discussions on the hydrochemistry of the Gulp Basin will be dealt with in a separate paper. (NOTA and BAKKER, in preparation.)

Summing up, the existence of springs and seepages in the area of active groundwater discharge is related either to the permeability contrast near the Gulpen-Vaals contact or to the fractured consolidated sandstones that occur

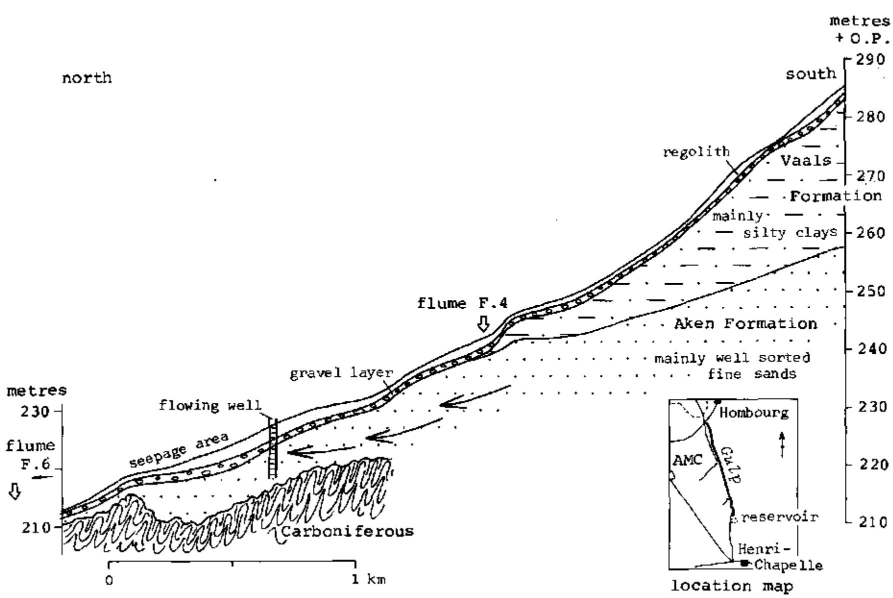


FIG. 7. A schematic geologic longitudinal section to show the hydrogeological conditions along the Gulp Creek in the study area.

below the Gulpen-Vaals contact. Variations in permeability and thickness of the regolith overlying the layered sedimentary formations and the interference of local relief and direction of groundwater flow cause the localization of springs and seepages. In this respect it is noteworthly to mention that the majority of springs and seepages along the roughly east-west tributary valleys is practically always found along the southern side, because of the flow pattern that is roughly to the north; otherwise, the part of the tributary valleys above the zone of groundwater discharge is dry.

(4) The *Aken Formation* occurs only in the northern part of the study area. Its surface extent is only small and is limited to the lower central part of the valley. The upper part of the formation that subcrops in the valley is composed of light coloured fine grained well sorted quartz sands (see previous section). There are a few domestic wells in these sands and the material is fairly permeable, though precipitates of iron hydroxide and silica may cause some anisotropy.

The present flat valley bottom is not more than 100 metres wide and the stream measures less than 3 metres across. The present stream bed was found to be in direct contact with any of the older geological formations only occasionally. The stream bed of the Gulp Creek practically always lies on top of a *residual gravel layer* with a maximum thickness of about 100 cm. The gravels consist mainly of angular chert and a few sandstones. The permeable gravel

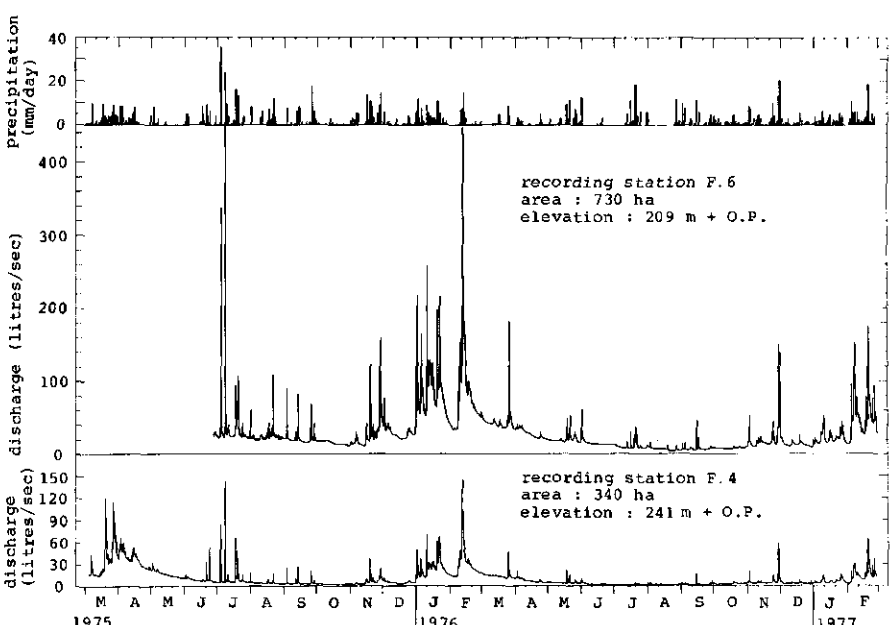


FIG. 8. Two hydrographs from stations F4 and F6 respectively, to compare discharges at different locations in the basin (cf. fig. 4); the hydrogeological significance is discussed in the text. Base flow comprises approximately 70 per cent of the total discharge. Levelling datum in Ostende Peil (O.P.).

layer is continuous underneath the present valley bottom and is considered as a relict of Late-Glacial time. It is assumed to have formed when periglacial melt waters with varying discharges reworked the valley fill with a braided system of shifting channels with a coarse grained lag deposit remaining.

Because of the presence of the gravel layer the Aken Sands will generally be in hydraulic contact with the Gulp Creek. This in its turn causes increased natural drainage flow through the Aken Sands towards the Gulp Creek; not only from that part of the study area where the formation subcrops in the valley, but also from upstream, where the formation continues under the subsoil (cf. fig. 7). As a result the pressure head in observation wells in the seepage area is above the level of the creek. This feature is reflected in the discrepancy between the measured discharges for two stream gauging stations: F 6 measures the total discharge of the study area (730 ha) and F 4, at about half way (340 ha), measures the discharge of the area upstream from the point where the Aken Formation subcrops in the valley (cf. fig. 8). The discharges measured between October 1st 1976 and September 30th 1977 for F 4 and F 6 were 327,648 m^3 and 968,606 m^3 respectively. The average discharge for F 4 and F 6 thus amounts to approximately 10 and 30 l/sec. respectively. The interception of the groundwater flow by the Veljaren tributary valley (cf. fig. 5), which is the major tributary valley in the area of study, is most certainly another contributor to the total discharge measured at F 6. However, the difference in measured discharge at F 4 and F 6 might also result from loss of groundwater out of the Gulp Basin in the upper part of the area (upstream F 4), as underflow to the Berwine or Geul system, or possibly recharge into the basement complex. Hence, additional measurements and further analysis will be necessary to quantify the various components for a hydrologic budget approach.

(5) The map and the cross section of fig. 4 indicate that there is *a fault along the western edge of the catchment;* actually the fault line and the topographical water divide nearly coincide. The existence of the fault in the study area was discovered during the field survey with the aid of hand borings and additional electrical resistivity measurements. The fault is most probably a continuation of what is known in the area as the Welkenraedt fault that offsets Carboniferous against Devonian rocks further to the south, between the villages of Henri-Chapelle and Welkenraedt.

The southeast-northwest direction of the fault is the same as is found elsewhere in the region, particularly in the adjacent areas to the north, in the southeastern Netherlands. Obviously it forms part of the northwesterly trending fault block structures that were active during the Cenozoic uplifting. The fault zones are considered to have developed from tensional forces (MONTFRANS, 1975), as a result of differential uplift.

Two features are apparent from fig. 4, (1) the fault offsets rocks of different permeabilities and (2) the fault block is tilted towards the west.

The fault offsets the relatively permeable chalk of the Gulpen Formation against the generally low permeable silty clays of the Vaals Formation. The fault most probably is not confined to a single fracture, but rather is a fault

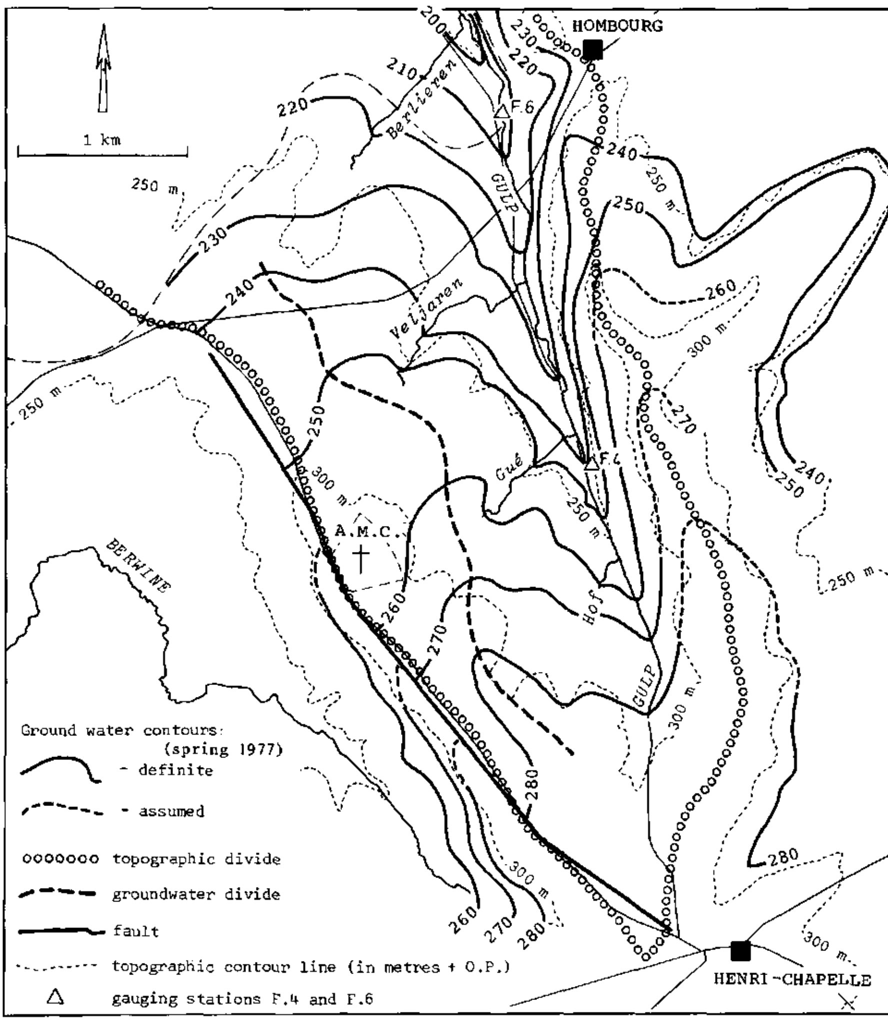


FIG. 9. Contour map of the groundwater table. Note the groundwater flow towards the fault zone and that consequently surface and subsurface catchment areas do not coincide; see also fig. 4.

zone with many tensionally produced and closely spaced fractures.

It can be expected that water circulating through the fractures and fissures has enlarged these passageways and thus will have caused an increase in the permeability. Faults within carbonate rocks are generally regarded as zones of higher permeability, though it is known that they are not in all cases (cf. SPANGENBERG, 1973, KASTNING, 1977). Here it should be emphasized, however, that permeability increase will have been primarily confined to the chalk side of the fault. The other side of the fault zone will have been plastered and thus more or less sealed off particularly by the clayey layers of the Vaals Formation.

It is thus considered that the ultimate result has been that *the fault forms a boundary to groundwater flow;* a boundary that acts to one side as a barrier while the other side (within the chalk) behaves as a preferential zone for groundwater flow. It is clear that the tilting of the fault blocks towards the fault together with the regional northwesterly dip of the geological formations in the study area will be particularly effective in the formation of *a fault-controlled zone of concentrated groundwater flow* that eventually discharges in a northwesterly direction.

There are several features that indicate such a concentrated groundwater discharge.

Firstly its existence is demonstrated by the *contour map of the groundwater table,* as presented in fig. 9. This map clearly shows that groundwater flows towards the fault zone and as a result that the topographic divide is not coincident with the groundwater divide. However, for the sake of completeness it should be mentioned that there were only a limited number of sites where the water level could be measured and that water levels have also been measured from a number of domestic wells that still are in use. Hence, the groundwater table map should be regarded as tentative and to represent only the general direction of groundwater flow.

Secondly, the occurrence of a series of *more or less linearly arranged dolines* and related features in the vicinity of the fault is striking (see fig. 10). The dolines vary in size from a few metres to more than thirty metres in cross section and show circular as well as elongated shapes; their depths range between two and more than ten metres. The occurrence of the dolines near the fault is considered to indicate that their development is associated with the increased fracture density and zones of increased permeability by subsurface dissolution in the vicinity of the fault. The concentrated groundwater flow in the fault zone will in its turn have influenced positively the formation of the dolines which thus have to be considered also as a surface manifestation from the erosion from below.

The presence of a *limestone spring* (the largest spring in the area, average discharge of about 70 litres per second) that issues from the Gulpen Chalk in the village of St. Pietersvoeren (Fouron-St. Pierre) situated in the Voer Basin and located along the trend of the fault mentioned previously, is considered as a third indication for *groundwater discharge out of the Gulp catchment.* (cf. fig. 10.) A reconnaissance field survey in the basins of the Veurs and Voer that are adjacent to the Gulp catchment has shown that there is a discontinuity in the stratigraphic contact between the Gulpen and Vaals formations along a line that coincides with the northwesterly continuation of the above fault zone. Although the available data indicate that there has been little noticeable displacement, tectonic deformation is evident. The Gulpen Chalk under the plateau remnants is more than 40 metres thick and groundwater levels in wells were found to occur within the limestone.

The tectonic deformation obviously has created favourable conditions for karstifications. The large number of dolines in the catchments of the Voer and

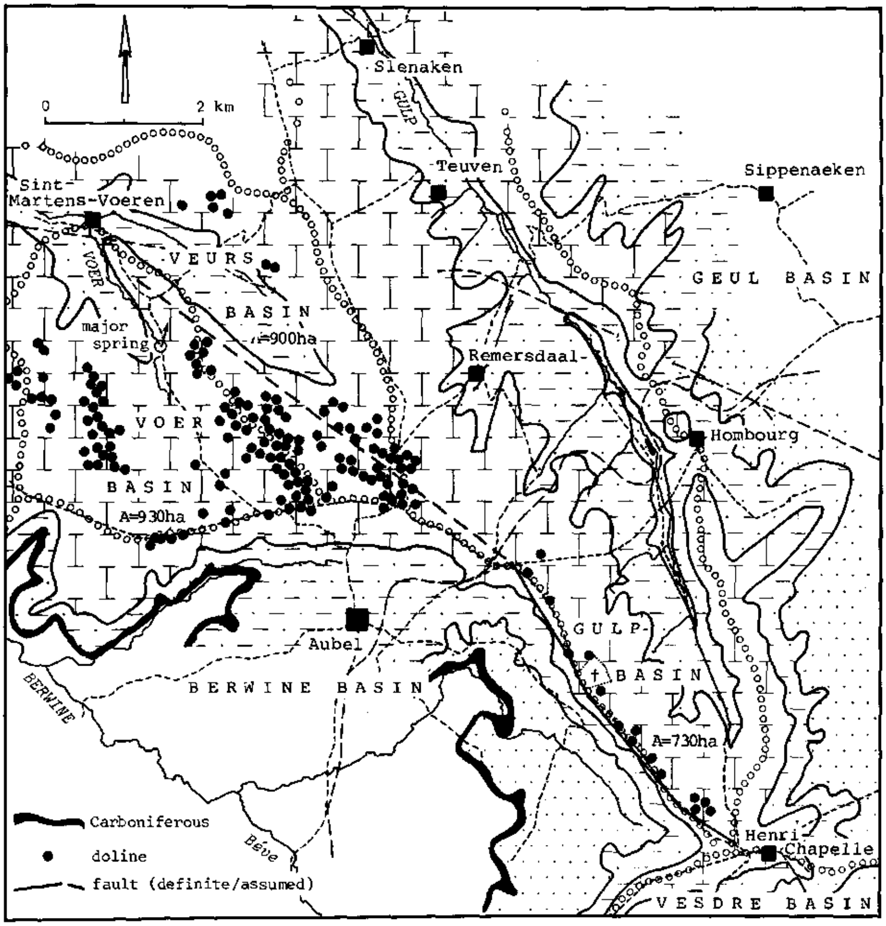


FIG. 10. Relationship between tectonic deformation, doline distribution and discharge differences for the basins of the Gulp, Veurs and Voer; for explanation see text. For stratigraphic legend cf. fig. 4.

Veurs, particularly upstream from where the groundwater has emerged to follow a surface course, is very striking. The *high doline density* in these catchments (cf. fig. 10), is considered to be related to both the structural deformation, to the well developed relief and to the recharge-discharge conditions. The groundwater recharge for the Voer and Veurs catchments is substantially increased by groundwater capture from the Gulp catchment along the fault-controlled subterranean discharge zone. This increase has been confirmed by discharge measurements at various times. Seasonal variations have shown that the largest discrepancies occur during base flow conditions, which is a result of the geological framework. The general regional tilting to the northwest acts during base flow most effective to divert the groundwater movement as an underflow beneath the topographic water divides towards the catchments of the Voer and Veurs. Catchment areas comparable in size for the Gulp (730 ha), Veurs (900 ha) and Voer (930 ha) basins showed discharges of 12 litres/second, 36 l/sec. and 84 l/sec. respectively during baseflow conditions (Nov. 1975). During the wet season (April 1976) values of 19 l/sec., 39 l/sec. and 70 l/sec. were found respectively; in April 1978 discharges of 52, 79 and 149 litres/second have been measured. These data clearly confirm other work in karstic limestone terranes, viz. that groundwater discharges per unit surface area in karstic stream basins (Voer and Veurs) are much larger than the zonal values of groundwater discharges within stream areas that have not or only slightly been affected (Gulp Basin) by kastification. (cf Le Grand and La Moreaux, 1975.) In this particular case, the karstification in the Gulp Basin along the fault system causes water loss, that eventually emerges in the basins of Veurs and Voer. This means that the Voer and Veurs catchments have extended their recharge areas onto the Gulp catchment as far as the movement of groundwater is directed towards the fault zone. A shifting of the groundwater divide as a result of seasonal fluctuations in groundwater levels acts in such a way that during the wet season high water levels, surface and subsurface catchment areas approach each other, whereas during low water levels the groundwater divide moves away from the topographic divide in a direction towards the valley of the Gulp Creek; however, *the fault zone acts throughout the year as a zone of subterranean drainage* towards the northwest and away from the Gulp catchment. It is worth mentioning that no groundwater tracing techniques have been applied in this study.

(b) *Topography and climate*

The other components mentioned in the beginning of this section (page 11) that characterize the hydrogeologic environment in the Gulp area, are the topography and the climate. The land surface of this dissected plateau landscape has a pronounced relief with relatively deep incised valleys. The stream incision that has occurred as a result of the regional uplift since the Late-Tertiary has created increased hydraulic head and thus increased groundwater circulation. This increased circulation and the position of the Gulpen carbonate rocks above river level have also created favourable conditions for karst development.

The climatological conditions in the area (see page 5) are such, that the interaction between precipitation, temperature and vegetation cover results in enough supply of water and CO_2 to maintain the formation of karst under present conditions.

Although topographic relief and climate are important hydrogeologic characteristics – particularly in relation to recharge and discharge circumstances – and the preceding discussions (under Geology) have clearly shown that the overall geologic setting is an extremely important factor, an understanding of the hydrogeologic system is only possible when the interrelationship among the various factors is recognized.

The general conclusions from a hydrogeological reconnaissance in the stream basin of the Gulp Creek are summarized as follows:

1. The Gulp Basin forms part of a dissected plateau landscape. Its geological history, the present relief and the properties of the various lithological units, in connection with the present climatological conditions, largely control the hydrological environment.

2. The gross lithology of the formations underlying the Gulp catchment is favourable for deep percolation and groundwater storage. Approximate separations of discharge hydrographs indicate that baseflow comprises some 70 per cent of the total discharge; the short extreme peaks are caused by paved surfaces, sewers and by interflow, (cf. fig. 8). The overall permeability of the catchment is well illustrated by the close relationship between the chemical composition of groundwater and surface water (cf. fig. 6).

3. Stream incision, tilting and faulting as a result of regional uplift since Late-Tertiary have been of vital importance in determining the surface and groundwater flow.

4. Stream incision has created favourable conditions for groundwater discharge. The effect of local differences in topography on the groundwater movement is best illustrated by the differences in localization of groundwater discharge along the steeper eastern and the more gentle western valley flank (cf. figs. 4 and 5).

5. Karst development in the Gulpen Chalk is localized; it occurs along the western edge of the catchment and is controlled by tectonic deformation. Its

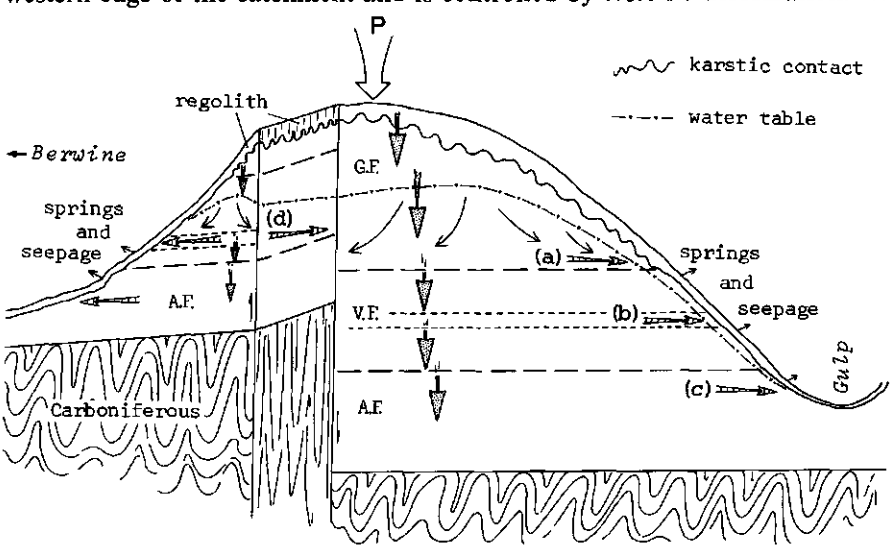


FIG. 11. Sketch of a conceptual hydrogeologic model in terms of groundwater flow, including factors of geologic structure, topographic relief and lithology; for explanation see under conclusions.

influence on groundwater movement is very important as it produces significant deviations from flow systems expected for homogeneous flow media. The northwesterly trending fault forms a preferential zone for groundwater flow; the fault zone acts as a drain along which a substantial water loss occurs for the Gulp catchment. As a result surface and subsurface drainage are not in the same direction and thus only part of the catchment will contribute to the base flow of the Gulp Creek. A limestone spring in the village of Fouron St. Pierre (in the Voer Basin) is a major outlet for the captured groundwater. This large limestone spring suggests that the Gulp Basin is not really a significant groundwater discharge area and that interbasin flow is a major factor. It is most probable after sudden recharge events such as spring snowmelts and heavy rainfall that the fault zone acts as a kind of conduit. Though such conditions have not been measured yet, long term observations are necessary to find out the characteristics of the flow system.

6. The occurrence and the general distribution of a large number of seepages and small springs in the area of groundwater discharge confirms that there is no major karst in the remainder of the catchment studied (cf. fig. 5); this means that in general within the Gulpen Chalk the groundwater movement is slow and diffuse.

7. There is hydraulic continuity among the Gulpen, Vaals and Aken Formations, because the Vaals Formation is not an aquiclude (see page 14). It should be emphasized, however, that there are zones of preferential groundwater flow. Groundwater discharge in the catchment takes place through these more permeable zones of least resistance (cf. fig. 11), viz. (a) near the permeability break between the Gulpen and Vaals Formation, (b) through the zones with fractured consolidated sandstones within the Vaals Formation, (c) through the fairly permeable Aken Sands and (d) along the western edge of the catchment through the kartstified fault zone. Each of these preferential zones of groundwater flow contributes to the drainage of the Gulp catchment, depending on the local topographic relief. The hydraulic continuity between the formations seems also supported by the available discharge hydrographs (cf. fig. 8), which do not show any discontinuity of the base flow – during extended dry periods like the summer of 1976 – that could be related to discharge from separate water sources.

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