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# African groundwater development — the challenges for hydrogeological science

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> *"sink in despair on the red parched earth,*
> *and then ye may reckon what water is worth"*

## GROUNDWATER: A VITAL RESOURCE

Groundwater has many advantages for water supply development. Aquifers underlie geographically large areas and can frequently be tapped close to the water demand, at least for smaller supplies, thus minimizing reticulation requirements. Water stored in aquifers is, for the most part, protected naturally from evaporation and the drainable storage is of substantial, and sometimes enormous, volume offering water-supply security in regions prone to protracted droughts. Given adequate aquifer protection, groundwater has excellent microbiological and organic quality, requiring minimal treatment. The capital cost of groundwater development is relatively modest and the land requirements minimal, the resource lending itself to flexible development capable of being phased with rising demand.

Such features make groundwater attractive as a source of potable supply, even in relatively humid climates. Given the vast extension and disperse population of rural Africa, it is not surprising that groundwater, and hydrogeologists, are beginning to play a major role in efforts to fulfil the objectives of the current UN decade. In the more arid regions, such as those within and bordering the Sahara and the Kalahari, the availability of groundwater resources will normally be the key to all development.

The principal hydrogeological problems in groundwater development are associated with:

(a) The difficulty in successful well (borehole) siting resulting from the geohydrological inhomogeneity of many minor aquifers.

(b) The estimation of the groundwater resources, that is, the recharge rate and exploitable storage, available for large-scale development in major aquifers.

(c) The occurrence of bodies of groundwater with unacceptable inorganic chemical characteristics in some aquifers.

It is from such problems that the challenges for hydrogeological science arise.

## GROUNDWATER INVESTIGATION: THE ECONOMIC CONSTRAINTS

Sensible economic constraints on groundwater investigation have to be recognized by hydrogeologists if they are to maintain credibility.

These constraints are determined by:

(a) The size, location and quality of projected water demand, which defines the required depth of knowledge of the local or regional groundwater system.

(b) The full economic value (opportunity cost) of proposed resource utilization which, in a general way, dictates the viable level of associated investigation.

Although public water-supply cannot be subjected to rigorous economic analysis, it has to be accepted that financial constraints have been a major factor retarding the implementation of groundwater development schemes desperately needed in Africa

### *Scale of water demand*

The demand created by rural potable water-supply and livestock watering needs is so small and dispersed as to require only knowledge of groundwater occurrence, since abstraction rates are unlikely to overtax the resources of minor aquifers, even those which may not have been recharged in recent history. In this context the occurrence of groundwater is taken to include the location and depth of the hydrogeologically productive horizon or zone, the groundwater quality, the piezometric level and thus the order-of-magnitude of available drawdown, well yield and pumping lift. Information on these factors will allow the prospect of successful boreholes to be assessed, development costs to be estimated and drilling site selection to be attempted. For progressively larger and more concentrated demands (including, by increasing order, those for minor urban, mining and industrial, supplementary irrigation, major urban and large-scale irrigation water-supplies), a more comprehensive knowledge of groundwater resources is required. In addition to the occurrence of important aquifers, quantitative information on their properties, storage and recharge are required on local or regional scale (according to the demand), for the design of wellfields, which may involve large numbers of high-yielding boreholes, and for the management of already heavily exploited aquifers.

### *Significance of economic return*

The influence that the economic return from proposed water use exerts on the viable level of hydrogeological investigation can be clearly illustrated by two, rather extreme, personal examples from the Botswana Kalahari. The use of groundwater search techniques for the siting of livestock watering boreholes (45 $m^3day^{-1}$ per 60 $km^2$) is only justified if they increase the chances of subsequent boreholes being more successful than "wildcat" drilling, such that the overall saving on drilling costs, in the long run, is greater than the cost of exploration; the ceiling on water-supply investment having been defined by the level of expenditure (including any subsidy) that livestock rearing can support to remain profitable (Farr *et al.*, 1982). It was demonstrated (Fig.1) that, for the given area under the prevailing local conditions, an absolute limit of US $5.5K per production borehole might be justified, although it would probably be more realistic to adopt a lower cost approach involving only

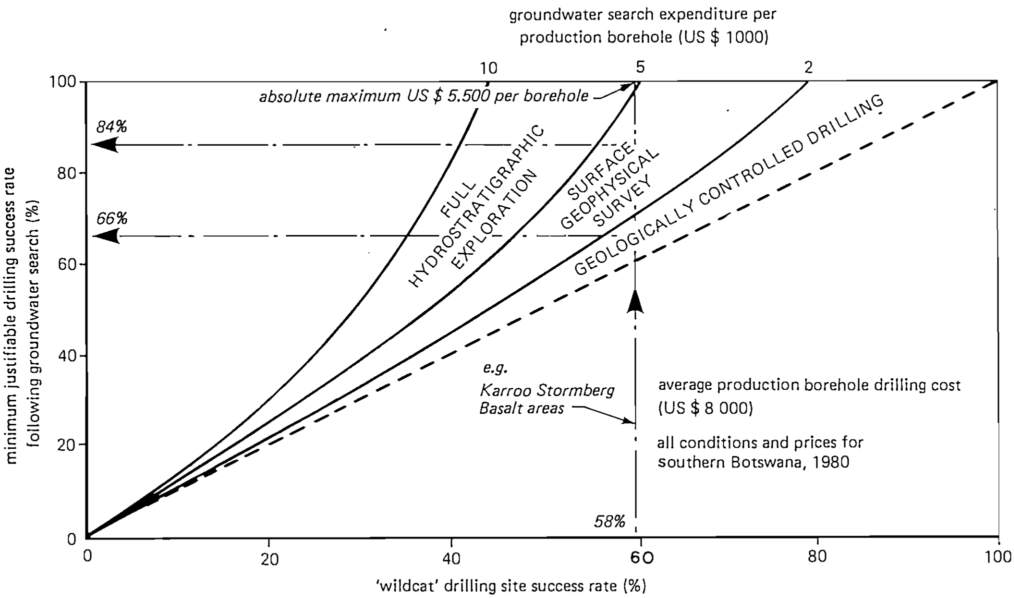

*FIG.1 Economic constraint on groundwater search for livestock watering boreholes (based on Farr et al., 1982).*

hydrogeological drilling supervision at a comparable unit cost of less than US $2.0K. On the other hand, a potentially highly-profitable mining development in an immediately adjacent area could support an investment of more than US $30M for a water-supply of 20 000 $m^3day^{-1}$ justifying an expenditure of about US $500K for preliminary groundwater reconnaissance (Foster *et al.*, 1982). Once reasonable groundwater prospects had been established, investigation continued up to a total expenditure of US $1850K, allowing the most comprehensive resource evaluation possible, given the prevailing time constraints, to rationalize development strategy and to facilitate wellfield design. The financial investment in groundwater investigation expressed in terms of area surveyed is only US $90 per $km^2$ in the former example and US $820 per $km^2$ in the latter, although in terms of water-supply requirement it is similar, in both cases, at around US $100 per $m^3day^{-1}$.

## *Relation between investigation and development*

Water-supply schemes are traditionally considered in three rather separate stages: investigation, design, and construction. In groundwater schemes these stages are more appropriately termed exploration, evaluation and development. While methods of groundwater exploration and evaluation are now well advanced, many are costly and time-consuming to apply, especially if precision is required. Thus, under African conditions, integrated groundwater schemes, in which these stages overlap with hydrogeological investigation active throughout, will generally be more appropriate. It is in such schemes that the most economical and technologically appropriate solutions to water-supply problems are likely to evolve.

When confronted by basic data deficiencies, project economic and time constraints, it is extremely important that a flexible and innovative approach to the hydrogeological investigation for groundwater development schemes is adopted. Investigation requirements can, to some degree, be reconciled with project limitations by:

(a) Clearly structured schemes, gathering information for the intensification, extension or modification of groundwater development from monitoring the operational performance of the initial (pilot) stages. For large-scale development, it is well to recognize that refinement of groundwater resource estimates may only be feasible by this approach.

(b) Concentrating most of the investigation funds economically justified by extensive small-scale groundwater development into research of a small area of representative geohydrological characteristics.

## THE SCIENTIFIC CHALLENGES VIEWED IN A GEOHYDROLOGICAL FRAMEWORK

It is helpful to consider the challenges for hydrogeological science, posed by groundwater development schemes, in each of the three principal African geohydrological provinces (Fig.2). Each province is characterized by a different scale of groundwater resource potential and by distinct groundwater exploration, evaluation, development and management problems (Wright, 1983).

### *Basement shield*

Very extensive regions of Africa are directly underlain by the crystalline basement rocks of the continental shield. Aquifers are developed (Fig.3) in the weathered mantle (sometimes known as the regolith) and in the fractured basement rocks themselves (often loosely referred to as the bedrock). Although not very productive, these aquifers are of increasing importance for rural water-supply, especially given improving hand-pump technology (Bannerman & Ayibotele*; Chilton & Smith-Carington*; Omorinbola*).

It now seems likely that the weathered mantle will generally prove the more consistent and less costly of these two interrelated aquifers to develop for small water-supplies, where the available drawdown to the most productive mantle horizons in drought is sufficient. This will be a function of geomorphological setting, bedrock type and present/past climatic regimes, since these factors will exert an interactive control on the depth of weathering, the present groundwater level and the extent of any aquifer removal by erosion. A fuller understanding of the evolution of weathered mantle aquifers and a unified conceptual model of their hydrogeology and hydrochemistry.is urgently required (Fig.3 is a preliminary step in that direction). From such a basis it should be possible to:

(a) Improve the criteria and methodology for siting boreholes to reduce yield failure during extended drought.

(b) Develop field techniques or operational methods to reduce the cost of borehole failure due to unacceptable chemical quality, related to the occurrence of elevated concentrations of fluoride,

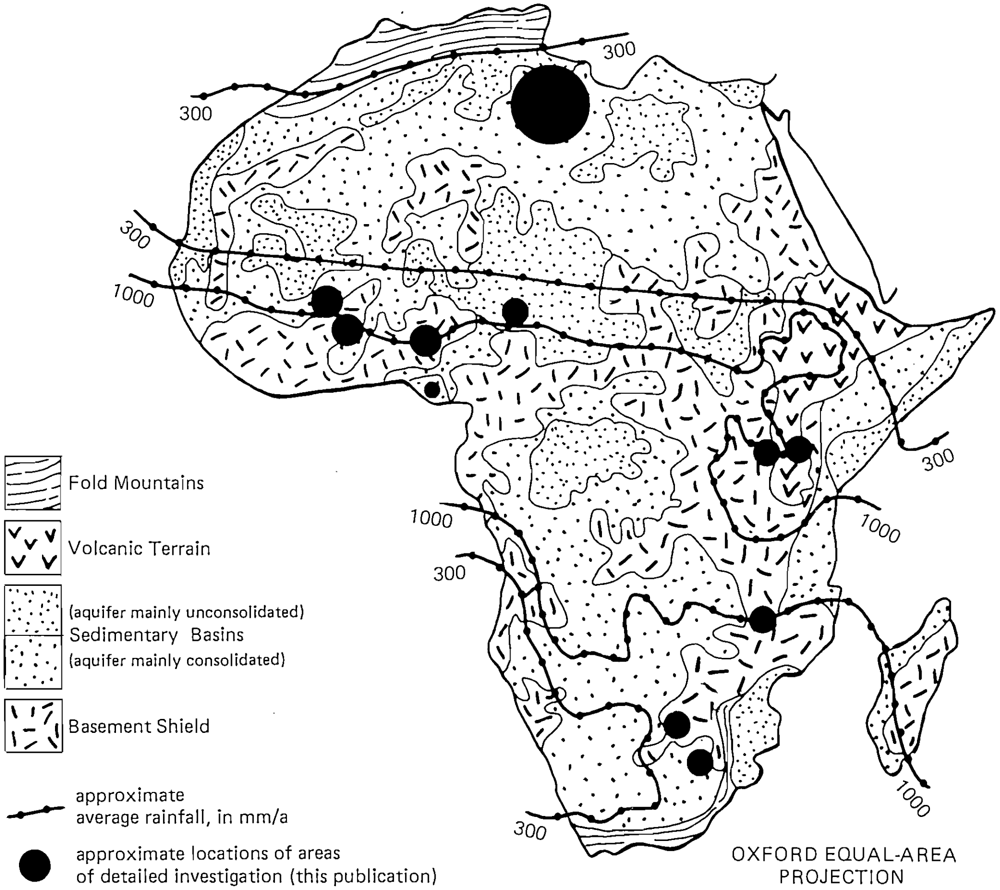

*FIG.2 Generalized geohydrological provinces of Africa (based on Wright, 1983).*

sulphate and magnesium, and to a lesser extent of soluble iron and manganese.

Where the weathered mantle aquifer is very thin or absent, the only possibility for groundwater development is the fractured bedrock (Buckley & Zeil*). The verification and refinement of rapid and economical remote sensing techniques, such as satellite image interpretation and combination of geophysical EM and ER survey, to locate productive fracture zones is the most pressing requirement here.

In some areas the weathered mantle and fractured bedrock aquifers may possess sufficient transmissivity to allow borehole yields adequate for motorized pumping plant, and the prospect then arises of groundwater utilization to supply smaller urban areas and/or small-scale supplementary irrigation. These borehole yields, however, can only be sustained if aquifer storage and recharge rates are adequate, and even the approximate estimation of these parameters in such inhomogeneous strata presents a formidable hydrogeological challenge. Progress will require the appropriate combination of a variety of traditional hydrogeological methods (accompanied by the

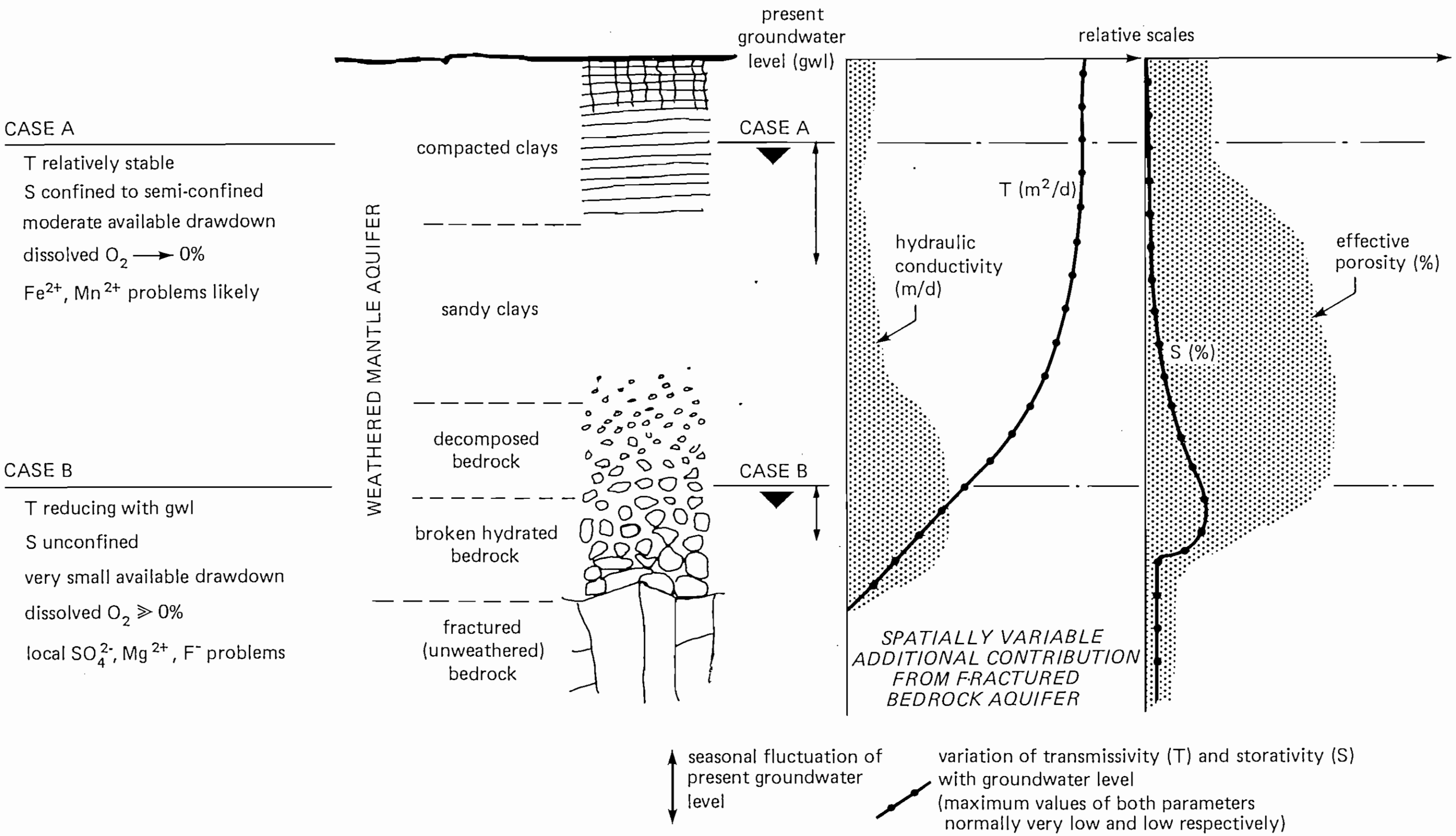

*FIG.3 Tentative conceptual model of weathered mantle aquifer of basement shield (developed from Chilton & Smith-Carington*).*

collection of the related basic data) (Singh *et al.**) together with the application of more modern techniques, such as environmental isotopes (Geirnaert *et al.**; Verhagen*). Research on improving the efficiency and capacity of production borehole design is also required to maximize the use of the invariably-limited available drawdown in the basement shield aquifers.

### *Sedimentary basins*

The sedimentary basins contain the most important and productive aquifers of the African continent and, at regional level, hold enormous volumes of water in storage. Other important, but more localized, sedimentary aquifers occur along some present-day valleys and coastal margins. Consolidated sandstone and limestone aquifers are normal in the older basins and those containing marine sediments, but unconsolidated aquifers are more common in the younger alluvial basins with terrestrial sediments. The former aquifers are frequently confined and artesian conditions may be present over large areas. The latter will tend to contain thick multi-aquifer sequences, whose overall long-term hydrogeological response is often unconfined.

In many parts of the main sedimentary basins, the possibility of large-scale groundwater development exists. Moreover, small-scale groundwater supplies can normally be developed quite readily, although borehole drilling and completion may be demanding and costly. The principal associated hydrogeological problems will include the initial exploration for major productive horizons to allow effective borehole siting and efficient borehole design, and the prediction of groundwater quality (especially salinity) (Oteri*), which can exhibit considerable spatial variation (in complex relation with geological, hydrogeological and palaeohydrological controls) and generally deteriorates at depth.

In the evaluation of required wellfield design and the assessment of impact of large-scale development, computerized aquifer mathematical modelling will be necessary (Llamas *et al.**; Pizzi & Sartori*). The determination of realistic values for the aquifer hydraulic parameters (transmissivity, storativity and especially specific yield), the establishment of the lateral aquifer continuity, and the estimation of active aquifer recharge (if any), constitute formidable hydrogeological challenges, requiring the combination of many techniques and painstaking fieldwork. Sensitivity analyses to errors in model parameter selection is an essential process guiding investigation priorities and wellfield design.

Much of the groundwater storage in the sedimentary basins of arid regions will be fossil, with concentrations of age dates in several known past pluvial periods. A fundamental philosophical question is whether, to what extent and under which circumstances, the mining of this groundwater storage should be encouraged, or at least permitted (Clark & Stoner, 1980). The observed groundwater levels and aquifer hydraulic gradients may reflect an equilibrium with present recharge or may still be adjusting to past climatic changes (Burdon, 1977).

### *Volcanic terrains*

Regions formed by volcanic rocks normally possess extremely variable aquifer occurrence and groundwater potential, reflecting directly the complexity of volcanic geology (Heederik *et al.**). Moreover, the natural chemical quality of volcanic groundwaters is rather variable and they may contain excessive quantities of minor elements such as fluorine (Nair *et al.**), boron and even arsenic. Some volcanic formations can be extremely permeable and comparable in behaviour to karstic limestone aquifers, due to the presence of lavas with major cavities and fissures. Others can be virtual aquicludes. While the approach to groundwater exploration, evaluation, development and management will be broadly similar to that for sedimentary basins, and resources may be sufficient to support large-scale abstraction in some cases, more limited aquifer extensions and higher development costs can generally be anticipated. Beyond this it is extremely difficult to generalize.

## PRACTICAL GROUNDWATER DEVELOPMENT AND MANAGEMENT ISSUES

### *Engineering aspects*

Although the groundwater content of this symposium is directed primarily towards the challenges for hydrogeological science, the interface of that science with the civil and mechanical engineering of production borehole drilling efficiency development, sanitary completion and pumping plant needs careful consideration in the context of groundwater development. Practical research on more economical drilling methods (both at low and high technological levels), on effective ways of improving borehole efficiency, on methods of improving wellhead completion to reduce or prevent direct borehole contamination (where the public and their animals must have access) (Lewis & Chilton*), and on more reliable, economical and easily-maintained pumping plant (both motorized and non-motorized) (Ward & Dunford*), are all of key importance in the efforts to increase the rate, reduce the cost and improve the efficiency of groundwater development for potable supplies.

### *Groundwater pollution protection*

The potential impact of agricultural cultivation (using increasing quantities of fertilizers and pesticides), of unsewered sanitation, and of certain other activities on groundwater quality must be recognized; a related need for an effective policy of aquifer protection to minimize groundwater pollution is evident.

### *Aquifer artificial recharge*

Where existing or proposed groundwater development result in the mining of groundwater resources, and where excess surface water exists as storm runoff or wastewater, artificial aquifer recharge should be considered (Jacenkow*; Paling*). There is a pressing need for closely-monitored pilot schemes to establish the feasibility, design and economics of artificial recharge, especially for intermittent runoff in semiarid regions using relatively simple recharge basin installations.

## SOME ORGANIZATIONAL AND PHILOSOPHICAL CONSIDERATIONS

### *National water (borehole) archives*

In many African nations the number of water boreholes drilled annually, by both public and private sector, will be expressed in thousands. If inadequate provision has been made for the collection, verification, registration and archiving of the hydrogeological data from all these boreholes (Sekwale*), a major and unnecessary loss of investment in that nation will have occurred, since the cost of obtaining the equivalent data by drilling investigation boreholes will be very high. The full documentation of unsuccessful water boreholes is of equal value in this context. Moreover, if an effective statutory requirement or financial inducement were devised for access to be provided in all successful boreholes for groundwater level measurement, this would greatly aid groundwater data collection at national level for relatively minor cost and inconvenience.

### *Multidisciplinary and multitechnical approach*

Most groundwater systems are complex, in consequence of the geological, hydraulic, chemical and biological complexity of subsurface environments. Therefore, they cannot be evaluated satisfactorily by the application of an individual technique alone or the collection of a data set for just a single parameter. The integrated interpretation of data collected by a variety of techniques is required. Thus, if fuller use is to be made of the more advanced techniques, such as satellite and airborne remote sensing and surface geophysics, chemical and isotopic determinations, geophysical borehole logging, computerized mathematical modelling, stochastic data processing etc., they should be deployed as an integral part of groundwater investigation projects and not in isolation, as too often continues to be the case.

Much effort is being put into low-cost groundwater development using relatively simple technology. However, it is a mistake to think that such low-technology development does not require some high calibre personnel, and cannot afford to support selective high-technology investigation. The cost of these vital inputs just has to be spread across a very much larger number of water-supply installations.

### *Role of hydrogeological science*

Since hydrogeology is a rather young multidisciplinary science, whose serious quantitative application is still relatively new to Africa, there remains misunderstanding in many quarters over what the science can do (and what it cannot do) for water-supply development, at least within sensible economic constraints. Hydrogeologists need to be more fully involved with the planning and management of groundwater projects, since input of hydrogeological knowledge is necessary at all stages for their efficient implementation.

Renewed efforts are needed at national and international level to communicate to planners, administrators and politicians both the vital significance of groundwater in potable water-supply development and the basic need for a different approach to groundwater development from that used for surface water. It is only through such understanding that appropriate organizational arrangements for groundwater development and hydrogeological investigation will emerge, and that the related projects will have appropriate resources and realistic structure. It is sincerely hoped that the symposium proceedings and this symposium publication will make a significant contribution in this direction.

> *"traverse the desert, and then ye can tell*
> *what treasures exist in the cool deep well"*
> (Eliza Cook, 19th century)

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