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GROUNDWATER MAPPING: A PREREQUISITE OF SUCCESSFUL GROUNDWATER RESOURCE ESTIMATION AND MANAGEMENT*

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SYNOPSIS

Resource management needs resource estimation. Resource estimation needs knowledge of the areal extent of related phenomena. The best representation of hydrogeological phenomena and their areal extent is the groundwater map.

An organized collection of basic data is a necessary base for the preparation of a groundwater map. Many data are available in files of authorities, offices and companies but a field survey is also necessary. Synthesis of basic data allows for representation of the following hydrogeological parameters on a groundwater map: distribution and properties of important aquifers; quantity, quality (physical and chemical properties), and movement of groundwater; groundwater table and other important groundwater characters and their changes in time.

An analysis of different map scales and methods of final representation (e.g. by individual map sheets, hydrogeological maps of natural or administrative units, national atlases) is given. Some published groundwater maps are evaluated. The necessity of mapping the seasonal change of the groundwater table in India (including a discussion of its engineering importance)is indicated.

The high ratio of salaries and wages to total cost is stressed. Whole or partial employment can be given to a number of geologists, engineers and to such non-specialists as teachers or students and also to a number of labourers.

1. INTRODUCTION

There cannot be any effective resource management without a reasonable estimation of the resource in question. Groundwater resource estimation needs knowledge of the areal extent of the related phenomena. Its best representation is the groundwater map. Therefore, groundwater mapping nowadays is on the increase. Such maps and atlases of differing scales, points of view and areal coverage are published or are under preparation on all continents. Their different aims and the different natural conditions result in a diversity of finished product, which is advantageous. Though the real pioneer times of groundwater mapping are over, its terminology, methods and ways of representation are not yet entirely consolidated, which is natural for such a relatively new branch of mapping. Less fortunate is the fact that "groundwater map" or "hydrogeological map" have become fashionable expressions and are often indiscriminately used on publications, even if they do not represent groundwater or are not maps at all. Geological maps with only a few, often vague or irrelevant, remarks on groundwater added to formation descriptions are not hydrogeological maps and will not be discussed here.

The expressions "groundwater map" and "hydrogeological map" are often used as interchangeable synonyms even in the same text. It is not necessarily so. Several kinds of map-type representations (technical, chemical, engineering, etc.) can be and are drawn without including the smallest geological

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reference (except, of course, that water is a liquid rock and, as such, it is part of the geology). I accept PFANNKUCH'S (1) definition (No. 892) of groundwater: "... that part of the underground or subsurface water that is contained in the zone of saturation." However, I am inclined to modify his definition of hydrogeology to: "... study of groundwater in its geological context." (It is disputable whether or not hydrogeology studies the unsaturated zone.) Therefore, it may be stated that a hydrogeological map represents groundwater conditions in their geological context. Of course, groundwater being a geological resource, must be dealt with in its geological context. The type of groundwater map to be used for resource estimation must be, therefore, a hydrogeological map.

2. PROPERTIES TO BE REPRESENTED

In the broadest terms, the groundwater map must represent the quantity, quality and movement of the available groundwater. Availability is a vague term with vistas towards technology, but still, as a rule, influences our selection of what should be presented and what should not. Quality means chemical (kind, quantity and ratio of dissolved materials, agressivity), physical (pressure, temperature and radioactivity) and biological (microorganism content) properties. The quantity, distribution and properties (type and percentage of effective porosity, transmissivity, permeability) of the aquifers are often used to characterize quantity and distribution of groundwater. Groundwater is a part of the hydrological cycle, which results in two related properties setting it apart from other geological resources: it moves and it is renewable. (It moves and is renewable, that is, even by the yardstick of an ephemeral human life.) The dynamism of groundwater also must be represented on a hydrogeological map: the direction of the movement as a minimum; and, if possible, its velocity. To represent areas of discharge and recharge is also important.

3. DIMENSIONS

A map is a two-dimensional surface. However, groundwater moves in a four-dimensional complex, i.e. in the three space-dimension and in time. The third dimension of depth may be added to the other two by the conventional tools of geological mapping: by profiles, block-profiles, superimposed sets of contour lines or by sets of maps representing different depths. The reconstruction of the groundwater flow conditions (represented by flowlines or by other methods) may be based on calculation, simulation, actual observations and measurements or, preferably, on their combination. The theoretical base for that is given by HUBBERT (2), electric analogue model by TÓTH (3), mathematical model by FREEZE AND WITHERSPOON (4), generalized from a great number of observations by ALMÁSSY in (5) and OZORAY (6, 7), and a good example of practical application is given by GERAGHTY (8). Study of groundwater chemistry is not only an aim in itself but also a tool to detect groundwater movement (CHEBOTAREV, 9; BACK, 10).

The representation of the time element, if needed, can be given by similar methods to those used by meteorology: maps of maximum, minimum, average or seasonal stand of the time-variable properties (in our case water table, piezometric surfaces, yield, recharge, discharge, temperature or chemical character), their maximum or average play (difference between maximum and minimum), and map of areal distribution of similar trends. Diagrams and cartograms (sets of diagrams, superimposed on a basemap) can be very useful, showing characteristics, e.g. the annual fluctuation of the water table.

4. COLLECTION OF BASIC DATA

The main steps of map-making are the collection of basic data, the construction of the map and finally its actual publication, our main concern being the first two.

The collection of basic data has two different aspects: collection of preexisting data and field work (the sensu stricto "mapping"). Both of them may be divided into first a temporary campaign of data-collection and then the permanent operations of data-storage and upkeep of an observation network.

Preexisting data of hydrogeological relevance are far more numerous than often believed. They include the geological, hydrological, soil- and groundwater-connected published and manuscript literature, topographic and geological maps and profiles, air-photos (maybe other remote-sensing techniques such as infrared imagery or space-photos as well), lithologic and electric logs of augered holes and boreholes from public authorities or private enterprises, meteorological data, hydrological data (such as rivers, lakes, reservoirs and irrigation characteristics, waterworks), and chemical analyses of groundwater. All available data on wells and springs must be collected. In some cases health authorities store great masses of chemical analyses, or electric companies list all the electrically operated pumps of tubewells, or engineering authorities store copies of permits to operate some types of wells. Drillers and well-diggers often keep records of their activities. Construction firms accumulate thousands of logs of augered holes and of water-table measurements. Municipal or mining authorities or irrigation companies may monitor groundwater levels for different purposes.

All the data, collected either from other authorities or directly from the field, must be recorded, put in order, preferably marked on work-maps and stored in permanent archives or in other data filing systems. Incoming data, such as measurements on permanent observation wells, new drilling reports, etc., are continuously added, thereby keeping the filing system up-to-date.

When the preexisting data are in order, they are evaluated. Maps and air-photos are studied (ROY, 11; MOLLARD, 12) and field work planned accordingly.

During the field work the expressions of both natural and artificial recharge and discharge are observed, measured or estimated, located on the map and recorded. These are (among others): sinkholes, springs, seepages, dry or wet depressions, marshes, alkali soil patches, mineral deposits from water, artificial recharge plants, wells, spring channels, mine or construction dewatering sites. Special circumstances (such as mineral, gaseous or hot water, caves, underground rivers, undrained basins, sea-water inundations) or special use of water (city or industrial supply, oilfield injection, health spas) are noted. The vegetation can also mark discharge areas (MEINZER, 13). An adequate number of water samples are collected for chemical analysis.

The most important data of a spring are: geological context, yield, temperature, deposit, colour, smell, perhaps taste; of a well: depth, technical data, lithologic log, geology of the aquifer(s), yield at given drawdown, groundwater level(s), temperature, performed tests (if any). Local people are important sources of information; they are asked about the year and circumstances of well completion, quality of water, yield, seasonal or irregular changes, drying up. Water levels, depths of wells, temperatures are measured and water samples are taken preferably by the mapping person himself.

To characterize the hydrogeologic properties of the aquifers (transmissivity, storage, long-term yield), actual hydraulic tests (DAVIS AND DEWIEST, 14; and WALTON, 15) are needed. If we are fortunate enough, there were proper pump tests performed on several wells within our mapping area. These data can be supplemented by calculation of apparent transmissivity and apparent long-term yield (OZORAY, 16) based on the less valuable basic data of the total drawdown after a given (usually short) time of pumping or bailing at a known rate. Lacking the quantity or quality of the above data, and for better interpretation, the groundwater mapping is supported by our own testholes and/or pump tests. It is in any case desirable but it adds to the cost.

The seasonal changes of groundwater conditions must be followed for at least one year by regularly checking a network of selected observation wells. The water table aquifer is especially sensitive to seasonality.

In India, for instance, because of seasonality of rains and of the influence of irrigation, the water table fluctuates greatly. It affects water supply from shallow wells, both for household purposes and for irrigation. Along the seacoasts it triggers a salt water encroachment, which also influences the construction methods of canals, locks and irrigation systems. A number of other engineering problems are also interwoven with groundwater seasonality: foundations of buildings and other heavy structures, construction of roads, railways, electric lines, etc.

A permanent observation well network helps groundwater mapping, the study of long-term hydrogeological processes and tendencies (including man-caused environmental alterations) and facilitates correlation of maps prepared in different years.

5. THE CONSTRUCTION OF THE MAP: SCALES AND METHODS

The scale of the final map depends on the extent of the area to be represented and on the quantity of the available data. The methods of the final representation depend on the aims of the mapping project and on the scale.

The mapping may extend to different project areas (a mine, a construction site, an irrigation system), administrative (a city, a county or district, a state or province, a country) or natural (a sub-basin, a watershed, or a mountain, a whole continent). A small project area may be covered by a single, large-scale map, or by a hydrogeological study with map illustrations such as that of JONES AND SUBRAMANYAM (17). Extensive areas may be represented by a single small-scale map, or usually by a few sheets such as in the case of the International Hydrogeological Map of Europe (see DEUTLOFF et al., 18). Such areas may also be covered by a set of medium or large scale maps published in a standard series as in the case of the 1:250 000 Hydrogeological Reconnaissance Map Series of Alberta, Canada (see OZORAY, 19), or bound together to form regional or national atlases such as the M.Á.F.I. (5), and the B.R.G.M. (20) or map-supported monographies (BROWN, 21).

It is advantageous to comply as closely as possible to the "International legend for hydrogeological maps" of the INTERNATIONAL ASSOCIATION OF SCIENTIFIC HYDROLOGY (22). The actual content and consequently the legend of each series of map, however, still will reflect the specific aims of the mapping project and the unique natural conditions of the mapping area: SEN SO-YUNG (23), BADRY (24). The elaboration of the legend is a key step towards the success of the whole operation.

The main content of a real hydrogeological map is a hydrogeological characteristic, expressed as a regional or formation average: yield, transmissivity, permeability or storage. It is represented by the most striking technical element of the map (by colour or by strong hatching, etc.). The geologic environment is also represented: formations, lithology, tectonics. Data-points such as wells and springs are given, as are the piezometric levels of one or more aquifer and/or the water table, flow directions, groundwater chemistry and maybe such related topics as present groundwater use, irrigation, hydrometeorology, soils. Much of this information is given on side maps, and hydrogeological profiles complete the map.

The representation technique of superimposing piezometric contours, flowlines and data points on geological maps is used, e.g. on the 1:50 000 French hydrogeological maps; data of groundwater use is also given (ROUX, 25). The detailed representation of the relevant morphology and underground hydrology, and the detailed hydrogeological description of the geological formations are the virtues of PALOC'S (26) 1:80 000 map. On the 1:500 000 Turkish maps the wells are shown by yield categories, determined at a standard 10 meters drawdown (TANVERDI, 27).

The 1:1 500 000 hydrogeological maps of Europe (DEUTLOFF et al., 18) give geological formations with lithological description, and their groundwater availability categorization by colours and piezometric contours.

The Hydrogeological Atlas of Hungary (M.Á.F.I., 5) shows yield as the main feature on 1:200 000 sheets by colour; lithology, tectonics and flow of groundwater, and chemistry and data points are given on separate sheets.

A systematic hydrogeological mapping of the Province of Alberta (BADRY, 24; OZORAY, 19) is currently in progress. Each standard 1:250 000 (for the unpopulated areas, 1:500 000) map sheet represents an area of two square geographic degrees, about 15 000 km^2, and is attached to a written report. The main map shows (superimposed on a topographic map) the average 20-year safe yields by colours, aquifer lithology by symbols, nonpumped water level of the most important aquifer by contours, recharge and discharge areas, flow direction, artesian basins, important data points (wells, springs). Four hydrogeological profiles show the vertical distribution of the same data as well as geological formations and chemistry by contours and diagrams. 1:1 000 000 side maps represent bedrock geology (including formation top contours), hydrometeorology, groundwater chemistry and data density.

A similar solution, a standard series of medium-scale hydrogeological maps with yield as the main content but including representation of the geological context would be suitable for India. (A single, very small scale map may give a final picture of the whole country.) The water-table aquifer and its seasonal changes should be more emphasized, however.

6. ADVANTAGES OF GROUNDWATER MAPPING

This paper started with the observation that groundwater maps are needed (via resource estimation) for effective groundwater management. Whoever prepares a groundwater-related resource inventory, keeps track of the present groundwater use, or plans expansion or changes in forms of use, conservation or environmental protection, requires groundwater maps. So does the city planner; the agriculturist; the soil, forestry, sewage, and liquid disposal expert; and the planning and construction engineer. (Think of such problems as construction of roads, tunnels, canals, power lines, protection against salt water encroachment.) Engineering geology in considerable part is based on knowledge of underground water conditions: an engineering geological investigation always includes groundwater investigation (OZORAY, 28). The mining industry also has a fundamental interest in groundwater conditions, as does every field-oriented natural science: geography, soil science, geology, geophysics, zoology, botany, microclimatology.

Many phenomena, otherwise unnoticed, are observed during mapping, which necessarily covers the entire surface of the target area. For example, the quasi-springs, the muskeg (marsh) fed, spring-like origins of creeks in the boreal climatic zone (OZORAY, 29) were identified during groundwater mapping. Attention is drawn to neglected problems, a precondition of their solution. This is an extra bonus for the science of hydrogeology. The mapping hydrogeologist continuously works in the context of the other natural sciences and tends to an interdisciplinary way of thinking (TÓTH, 30).

The mapping operation may start with a small core of experienced hydrogeologists and it is an excellent opportunity for on-the-job-training. Great, unused energies and abilities can be mobilized and directed towards useful purposes during a widespread mapping operation. Many wholly or partly unemployed persons can be usefully employed at three levels:

a) geologists, engineers, chemists, cartographers, trained drillers, draughtsmen (in their special fields);
b) intelligent middlemen (including part-time unemployed people such as teachers and students during vacation periods) for local inventory-taking, data collection; and local part-time contractors or employees for such jobs as checking permanent observation wells in their villages;
c) physical workers such as drillers and installers, porters, drivers, office helpers and such.

The ratio of salaries and wages to total costs is very high. Once the framework of the project (headquarters, laboratories, vehicles) is established, 75 per cent or more of the total operational costs (allowing for gasoline, repairs, stationery, etc.) can be spent on wages and personal expenses. This is a very advantageous feature for countries with unemployment problems, particularly for unemployment within the intelligentsia.

Thinking particularly of India, it is the author's opinion that both the need for the hydrogeological mapping of the country and the ability to perform this huge task are present. The evidence of several E.T.O. (Exploratory Tubewells Organization), Geological Survey and United Nations groundwater projects supports this opinion. This project also has global merit and interest because until now hydrogeological mapping of extensive areas was essentially restricted to the temperate zones. Hydrogeological mapping over vast tropical and subtropical areas would greatly add to human knowledge.