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ARTYKUŁ PROBLEMOWY

From simple cross-sections and piezometry to 3D interactive models and the modern concept of interdisciplinary interrogation

Od prostych przekrojów i map hydroizohips do trójwymiarowych modeli interaktywnych i nowoczesnej koncepcji interdyscyplinarnych badań

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Abstract: Hydrogeological mapping evolved from simple cross sections and piezometry to elaborate colour printed maps at regional and national scale. These 2D depictions of a 3D system were limited in the amount of real detail they could show and were difficult to interpret, especially by non-specialists. Nowadays, a 3D visualisation package can be employed to better display the real shape of the geological structure and the aquifers contained within it. Other data, including time series information, can be loaded within the visualisation model so that it can be used as a data platform on which to mount analytical software. This allows much more realistic geological information to be encapsulated in analytical models. As hydrogeology becomes more and more interdisciplinary so the hydrogeological data and related analytical codes can be linked to those in other relevant areas: for example, climatic, environmental and social. The future of analytical hydrogeology is bright, but lets us not forget that it is the understanding of the geological setting that underpins the science.

Streszczenie: Kartowanie hydrogeologiczne ewoluowało od prostych przekrojów i map hydroizohips do opracowania wydrukowanych w kolorze map w skali regionalnej i krajowej. Te dwuwymiarowe obrazy systemu 3D były ograniczone pod względem rzeczywistych szczegółów, które mogły zawierać i które były trudne do zinterpretowania, zwłaszcza przez osoby niebędące specjalistami. Obecnie można zastosować pakiet wizualizacji 3D, aby lepiej odzwierciedlić rzeczywisty kształt struktury geologicznej i warstw wodonośnych w niej zawartych. W modelu wizualizacji mogą być zawarte inne dane, jak np. informacje o szeregach czasowych, dzięki czemu może być on wykorzystywany jako platforma danych wyposażona w oprogramowanie analityczne. Pozwala to na umieszczenie znacznie bardziej rzeczywistych informacji geologicznych w modelach analitycznych. Wraz ze zwiększaniem się interdyscyplinarności hydrogeologii dane hydrogeologiczne i związane z nimi kody analityczne można powiązać z danymi w innych obszarach, takich jak na przykład klimatologia, środowisko i nauki społeczne. Hydrogeologia analityczna ma przed sobą świetlaną przyszłość, ale nie należy zapominać, że u podstaw nauki leży zrozumienie środowiska geologicznego.

Key words: hydrogeological mapping, history, current state and future
Słowa kluczowe: mapy hydrogeologiczne, historia, współczesność i przyszłość

INTRODUCTION

The modern 3D interactive model portraying hydrogeological features within a realistic geological framework is the direct descendant of the conventional geological and general hydrogeological map. Hydrogeological maps have been widely used as the backdrop for GIS format databases to facilitate interrogation of data both aerially and according to aquifer type. The power of modern day digital imagery means that there is no longer a need to produce finely crafted and handsomely printed coloured maps. It also means that by linking the digital map to the underlying database, the map or model is automatically updated. It is these dynamic products that in turn can be applied as data platforms to drive a variety of analytical models.

Such advanced technology has only recently become available while obsolescent hard copy paper maps and cross-sections are now beginning to be condemned as

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artefacts. Tracing the lineage of hydrogeological and related thematic mapping from the mid-Victorian era to the present day exposes some colourful characters and a host of even more colourful maps. In Britain it is convenient to think that the father of the hydrogeological map was Joseph Lucas (1846-1926), but in reality others were already leading in the field with Russian groundwater maps developing from the mid-eighteenth century while both the French and Americans were also a little ahead of Lucas. Indeed work in the Paris Basin is believed to have influenced Lucas in defying his boss, who had charged him with geological mapping in Yorkshire, northern England, while Lucas preferred to map piezometry in the London Basin in the south of the country (Mather et al. 2004).

The hydrogeological map evolved through the twentieth century into a compact graphical presentation of the hydrogeological understanding of a given area. The central graphic is the map itself, based to a large extent on the available geological map, accompanied by a variety of inset graphics and text explanations including selected time series data. Although a standard international legend was established (e.g. Anon 1970) individual hydrogeological maps were made and presented for a variety of purposes to a variety of audiences so that the range of map types was broad. At the same time specialist thematic maps were produced, including groundwater vulnerability and groundwater potential maps (Fig. 1) which ranged in cartographic quality from simple line work, such as the Hydrogeological Map of Malawi (Department of Surveys 1987), to complex and highly technical coloured maps such as the 1: 125 000 scale Hydrogeology Map of South Wales (British Geological Survey 1986). More recently paper maps have been overtaken by interactive digital maps with a departure away from conventional 2D map format to a user-friendly 3D model format.

This review paper describes the evolution of the hydrogeological map and the progress of the interactive 3D data platform. It starts with the early monothematic maps and cross-sections through to the modern thematic maps and 3D digital portrayals of hydrogeological data within a comprehensively defined geological environment. A key objective is to highlight the importance of the geological setting in understanding both groundwater transport and storage and to highlight the importance of the geological overview in modern day groundwater mapping and modelling.

THE ANTECEDENTS

By 2000 BP the people of Asia and Persia were familiar with the concept of hydraulic gradient sufficient to engineer the qanat or tunnel draining under gravity towards a water supply tank. Their descriptions of groundwater flow, however, only went as far as vertical schematic slices or cross-sections that illustrated the role of gravity.

The first attempt at assembling large scale groundwater data in map form is credited to the Russian Academy of Sciences which had been established by Peter the Great in 1724. The Academy directed several expeditions to collect information on natural resources. These were focused on the Ural Mountains, Siberia, the Volga basin, the Kolsky and Kamchatka peninsulas, the Dnepr basin, and the Caucasus. Each expedition collected data that included the occurrence and distribution of fresh water and mineral springs, groundwater elevations, the relationship between groundwater chemistry and chemical composition of water-bearing formations and the role of groundwater in karst processes. The results from the first expedition, carried out between 1733-1743, were published in the monograph Description of the Land of Kamchatka (Krasheninnikov 1765) which contained numerous cross sections and thematic maps with accompanying descriptions of both surface and groundwater features including mineralised and fresh water springs (Zaltsberg 2013).

It was a long time before this early form of mapping translated to other countries and it only did so as need arose. In France maps of the Paris area were published by Delesse (1858) showing water level contours in three separate aquifers at a scale of approximately 1: 6700. A larger area of the entire Département de la Seine was subsequently mapped to similar criteria (Delesse 1862). In North America the need to understand artesian groundwater systems to supply irrigation schemes without the need for a steam pump was an essential technical development (Meyer et al. 1988). In Britain the need to understand groundwater flow processes only emerged when water stored in the Chalk aquifer in the London Basin became a tenable economic asset in the

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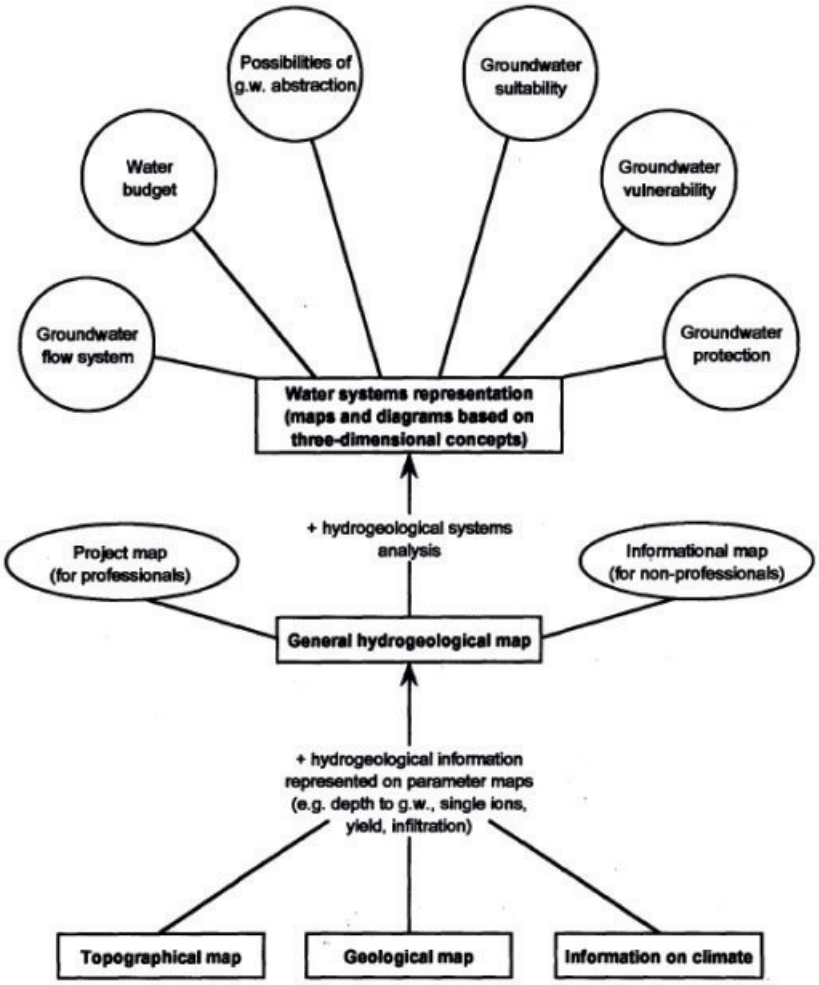

Figure 7. Evolution of hydrogeological maps.

Fig. 1. The family of maps (after Struckmeier 1989)
Rys. 1. Rodzina map (after Struckmeier 1989)

1870s. Joseph Prestwich (1812-1896) published his seminal cross-sections of the Thames basin 'shewing the extent of the water bearing strata, the position of the more important springs, and the head of water on which those springs and the streams they feed depend' (Prestwich 1870). Joseph Lucas was the first in Britain to gather groundwater level data into contoured piezometry in map form (Lucas 1874, appended Map A and Map B). Map A shows, for the first time in Britain, groundwater level contours measured 'early in 1873' and 'at the end of 1873' clearly identifying the transient nature of the water table over an area of about 120 square kilometres.

Time series data are an important component of the hydrogeological map although only a few records of weekly or daily manual dipped data commenced in the nineteenth century. The first record of automatic continuous water level recording was that at Oyster Bay in Long Island Sound, New York in June 1903 (Veatch 1906). The equipment comprised barograph stands and a barograph cylinder driven by a double spring clock and a lever with a pen at one end and a means of attaching a float at the other. It was used in an investigation on sea tides on a confined coastal aquifer. The length of the lever provided the ratio between the recorded hydrograph and the actual water level fluctuations.

Groundwater chemistry soon also developed into a major sub-set within hydrogeology and both areal distribution of ionic concentrations and variations with time were included in the marginalia of many hydrogeological maps. The maps themselves became ever more complex, some in the mid-twentieth century depicting extent of sea water intrusion, others highlighting the occurrence of mineralised discharges.

In the late 1940s there started a major effort to document resources in Britain and this led to a significant effort being put into mapping. By way of example, The Hydro-geological Survey of Kent (sic), carried out by Henry Lapworth Partners for The Advisory Committee on Water Supplies for Kent in 1946 yielded a series of separate thematic maps at a scale of 2 miles to an inch (~1: 31 680) which included depths to the top of the Palaeozoic, Greensand, Gault and Chalk, long term average rainfall, groundwater level contours, borehole sources and catchment areas.

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Another major effort commenced in the late 1970s when the UESCO International Hydrogeological Map of Europe was compiled and published in collaboration with Bundesanstalt für Geowissenschaften und Rohstoffe. Thirty map sheets were produced at a scale of 1: 500 000, each with an accompanying description (e.g. Aldwell et al. 1978). Meanwhile the Geological Survey in Britain embarked on a rolling programme of hydrogeological map production at scales varying between 1: 625 000 (national scale) and 1: 50 000, the majority of the 23 map sheets being to 1: 100 000 scale (regional scale).

A key problem was how to deal with confined aquifers. The geological map as the basis of a hydrogeological map shows only the rocks at outcrop, some with Quaternary cover, where it is extensive, removed as a second map layer. A confined aquifer, by definition is not exposed at surface and only features on a geological map in cross section or textual marginalia. A number of devices were created to deal with this problem, the impressive French 'pyjama stripe' colouring of a sequence, for example, denoted an unconfined aquifer over a confined aquifer as a single unit. But none of these techniques were wholly satisfactory and all required intelligent interrogation and an understanding of the logic of geometry. Fit for purpose for professional consumption they were, but they were of little use for informing the lay person.

Technological advances in computing, data handling and assembly led first to the 3D geological model and then to the issue of how to load hydrogeological data into that geological environment (Royse et al. 2010). Planar data such as piezometry could be loaded as a surface additional to the geological surfaces within the model although subject to different constraints. Distribution of physical properties data can equally be loaded as 3D planar contours although such data are rarely available in sufficient quantity and adequate reliability. But much hydrogeological data relate to aggregate values from a borehole column rather than a single point in space, i.e. a vertical dimensionless line, the modelled length of which is given by the depth of the borehole; such data are not easy to present graphically. The other problem was how to deal with the fourth dimension so that time series data could also be loaded, a problem now largely solved through use of the GIS data holding format.

ROLE, OBJECTIVES AND FAILINGS OF HYDROGEOLOGICAL MAPS

2D Hydrogeological maps

Collin (1989) defines the role of the hydrogeological map: 'A map is (and always will be) a tool of information transfer, for decision making and other uses depending on the scale, and in the broad sense, an educational tool'. As for 'decision makers', Collin continues: 'they rarely express their demand in cartographic terms, but simply request techno-economical information, sometimes in terms of space'. Hydrogeological mapping is a consequential response to this demand, but one which appears to be constrained by hydrogeologists' leanings for the 'techno' rather than the 'economical'. Struckmeir (1989) defined the objective of 2D hydrogeological map compilations 'to synthesize the available information on the hydrogeological conditions and groundwater in order to develop an overview of the regional hydrogeological setting of an area', whereas areas with abundant data used the map 'for conveying the professional hydrogeologist's information to planners, executives and the public...'. These definitions lead to the obvious failing of most hydrogeological maps, that they were prepared by hydrogeologists for hydrogeologists with inadequate regard for the need of the less technically endowed user community. But that in itself is not strictly a failing of the map rather of its compiler.

The key role for the 2D hydrogeological map, as far as the hydrogeologist was concerned, was that it greatly assisted in resolving a conceptual flow model for an aquifer system as it was a synthesis of all that was known about the aquifer, its constraints and its geological setting (Robins et al. 2005). The conceptualisation process is the realisation of a broad understanding of the hydraulics of an aquifer, encompassing the geological framework, prevailing hydraulic gradients, centres of recharge and discharge and any know boundaries. But again, the issue was how to prepare a 3D conceptualisation from a 2D plan in which it was not possible to view the conceptualisation together with the geological framework.

2D hydrogeological maps fail in general, as do 2D geological maps, simply because they are trying to present a 3D picture in plan form, albeit usually assisted with cross-sections. The 2D geological map, for example,

is a mapping geologist's attempt to bring his 3D vision of the pile of rocks he is mapping at surface down to a 2D image which the user then has to interpret to again visualise the whole picture in 3D. But for many decades that was the state of technology and little could be done to progress to 3D until computer modelling codes became available in the 1980s. The 2D hydrogeological map was, for the most part, based on the 2D geology map but with a hydrogeologically meaningful legend in place of the usual lithostratigraphical labels. As such these maps were constrained by the geologist's original portrayal of the 3D system in plan form.

3D Hydrogeological models

3D hydrogeological models use conventional visualisation software (e.g. CAD, VULCAN) as the platform to develop a comprehensive image of the geological framework for a given area. Preparation of the visualisation model is labour intensive and time consuming, but once done the model can be applied to many uses time and time again. The hydrogeologist uses the geological visualisation model to load the pertinent hydrogeological data, principally the shape and form of the aquifers he wants to study, as well as all the analytical data that are available. By linking the model data system to the data archive, the model data can be automatically updated as new information become available. The model can be used to depict planar surfaces such as piezometry, or even contoured concentrations of selected ions and, of course, can highlight pollution hot spots and other hazards. It is not only a visual representation of the understanding of the hydrogeological regime but also a data platform on which analytical software such as MODFLOW can be linked. By doing this, the logic of the geometry of the geological setting is assured from the visualisation model and, therefore, so is the logic of the shape of the aquifers themselves.

Having overcome the difficulties of representing the aquifer in an analytical model the only other data issue is the representativeness of the data and the risk of using skewed data sets. A common skew factor is that of borehole yields – few borehole yield data sets include blank or very low yielding boreholes and this provides a positive spin on the data set.

THE FUTURE

Understanding the geological setting of any hydrogeological province remains paramount to sensible interpretation of the hydrogeological regime. Using 3D visualisation software as a platform to run analytical models enables 'what if' questions to be asked in the knowledge that the geological information is broadly correct, and not as is so often the case, portrayed as a simple slab of porous medium with a defined top and bottom along with leakage characteristics and, possibly, adequately defined vertical boundaries. Such estimation of reality is no longer acceptable as it leads to serious errors and ultimately to the provision of misinformation being provided to the end users such as the resource managers. Thus, a key step forward has already been made – that of sensibly and accurately capturing the geological framework as the foundation for the overall hydrogeological system.

The future is exciting. Hydrogeology is increasingly moving towards interdisciplinary studies involving climatological, environmental, social and other areas. These all require detailed interaction so that the social constraints and demands can be interrogated by the environmental, and climate change predictions loaded into any or all of the separate disciplines. This is now possible through conjunction of a set of models, each able to interrogate the other and ask the other to run data analyses to support the analytical programme of the next model. At the bottom of the pile of models sits the 3D data platforms, one for hydrogeology, perhaps one for hydrology and environment (ecology, habitat) one for climatology and one for sociology. Sounds complicated? Not really, work is already well advanced in creating such modelling arrays. The human element must not be forgotten and the output needs to be checked against simple logic and probability determination codes with uncertainty quantified for each output.

CONCLUSION

It must always be remembered that hydrogeological understanding depends firmly on geological understanding and a broad feel for the quality of the data being used. The 2D printed paper maps of hydrogeological systems have now been overtaken by modern 3D visualisation models that better depict the geological data. These provide valuable data platforms on

which to found analytical programmes, and these in turn can be linked to other analytical programmes, similarly founded, working in related disciplines.

REFERENCES

Aldwell C.R., Day J.B.W., Stuckmeier W., 1978 − Explanatory notes for the International Hydrogeological Map of Europe, Sheet B4, London. Bundesanstalt für Geowissenschaften und Rohstoffe, Hannover and UNESCO, Paris.

Anon, 1970 − International legend for hydrogeological maps. UNESCO/IASH/IAH/Institute of Geological Sciences, London.

British Geological Survey, 1986 − Sheet 17, 1: 125 000 scale Hydrogeology Map of Wales. BGS, Keyworth.

Collin J.J. 1989 − An attempt to evaluate the socioeconomic impact of hydrogeological maps. [in:] Memoires of the International Symposium on Hydrogeological Maps as Tools for Economic and Social Development. Hannover, pp. 319-321.

Delesse A.E.O.J., 1858 − Carte hydrogeologique de la Ville de Paris. Paris, Office of the Prefet de la Seine.

Delesse A.E.O.J., 1862 − Carte hydrogeologique du Départment de la Seine. Paris, Office of the Prefet de la Seine.

Department of Surveys, 1987 − Hydrogeological reconnaissance maps. 1:250 000 scale in 9 sheets. Department of Surveys, Blantyre.

Krasheninnikov S., 1765 − Description of the land of Kamchatka. Saint Petersburg.

Lucas J., 1874 − Horizontal wells. A new application of geological principles to effect the solution of the problem of supplying London with pure water. Edward Stanford, London.

Mather J.D., Torrens H.S., Lucas K. J., 2004 − Joseph Lucas (1846-1926) – Victorian polymath and a key figure in the development of British hydrogeology. [in:] J.D. Mather (ed.), 200 years of British hydrogeology. Geological Society, London, Special Publications, 225, pp. 67-88.

Meyer G., Davis G., LaMoreaux P.E. 1988 − Historical perspective. [in:] W. Back, J.S. Rosenshein, P.R. Seaber (eds.), The geology of North America. Volume O-2. The Geological Society of North America, Boulder, US-CO.

Prestwish J., 1870, Report of the Royal Commission on Water Supply. Ordnance Survey Office, Southampton.

Robins N.S., Rutter H.K, Dumpleton S., Peach D.W. 2005 − The role of 3D visualisation as an analytical tool preparatory to numerical modelling. Journal of Hydrology, 301, 1-4, pp. 287-295.

Royse K.R., Kessler H., Robins N.S., Hughes A.G., Mathers S.J., 2010 − The use of 3D geological models in the development of the conceptual groundwater model. Zeitschrift der Deutschen Gesellschaft für Geowissenschaften, 161, 2, pp. 237-249.

Struckmeier W., 1989 − Types and uses of hydrogeological maps. [in:] Memoires of the International Symposium on Hydrogeological Maps as Tools for Economic and Social Development. Hannover, pp. 17-30.

Veatch A.C., 1906 − Fluctuations of the water level in wells, with special reference to Long Island. Department of the Interior, United States Geological Survey Water Supply and Irrigation Paper 155, Series 0, Underground Waters.

Zaltsberg E., 2013 − 250 years of Russian hydrogeology (1730-1980). [in:] N. Howden, J.D. Mather. History of Hydrogeology, International Association of Hydrogeology International Contributions to Hydrogeology, 28, pp. 243-256.