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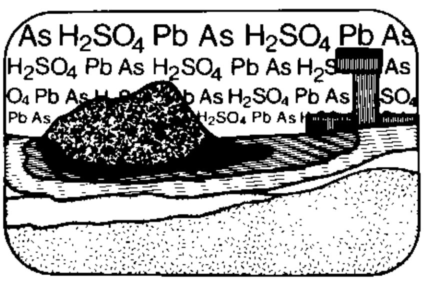

Groundwater Quality

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Introduction

For three days during September 1976 the Water Research Centre of Great Britain was host to a conference entitled "Groundwater Quality - Measurement, Prediction and Protection" at the University of Reading, England. The purpose of the conference was to consider current and future problems in groundwater quality management, the hydrogeological and geochemical processes governing groundwater pollution, the collection of field data, their processing by computer-based simulation models and the protection and rehabilitation of aquifers.

The program consisted of 22 invited papers, two field trips and a workshop on groundwater quality models. A large number of unsolicited papers were preprinted and distributed to the audience, as were the invited papers. Of the invited speakers five were Americans, two were Dutch, two were Israelis, one was from West Germany and the rest were from Britain. The fact that none of the 10 foreign speakers was a Canadian offers us an independent assessment of our achievements, although Canadian mathematical modellers were on several occasions cited by the speakers.

The Big Picture

The opening session presented three views of the problem of groundwater quality management. G. P. Jones of University College, London stressed the heterogeneity of British aquifers and warned against the simplifications of the pagan modellers who were to follow him to the podium!

J. W. Keeley (EPA, Ada, Oklahoma) summarized the principle contaminants in U.S. groundwaters (chlorides, nitrates, heavy metals and hydrocarbons) and the sources of groundwater pollution - septic tanks, brines associated with petroleum extraction, poor well construction, highway de-icing salts, etc. Of the other sources such as sanitary landfills and industrial waste lagoons, Keeley made note of the difficulty of sampling and analysing those substances or parameters which are not ordinarily considered in groundwater investigations. He continued: "When we realize that the subsurface transport processes of these parameters and their degradation products must be understood before adequate waste management schemes can be undertaken, our problems are exponentially complicated".

With such thoughts in mind it is not surprising that many speakers stressed the need for groundwater protection rather than restoration. Professor Huisman (Delft) presented a discussion of the aquifer protection schemes common throughout Europe whereby the recharge areas of important well fields are divided into zones on the basis of the travel time from infiltration to artificial abstraction. Within each of these zones industrial, agricultural and domestic waste-producing activities are carefully prescribed or prohibited.

Matters Theoretical

The second session, on the concentration and movement of pollutants, consisted of four papers presenting reviews of the hydrogeological, microbiological, geochemical and hydrodynamic aspects of contaminant transport and attenuation.

In the first of this group of papers Brereton and Wilkinson (Water Research Centre) discussed the hydrogeological controls on the migration of pollutants in both intergranular- and fissure-flow environments. It was particularly fascinating to find British thinking on the nature and magnitude of the dispersivity coefficient and on the processes of contaminant migration in fractured media so in harmony with that in Canada. The British authors had come to the conclusion that the order-of-magnitude differences between laboratory column and field tracer measurements of the dispersivity coefficient must be due to existence of major heteorogeneities in the aquifers being tested. Whereas Canadian thinking on this topic has been mostly influenced by the laboratory models of Skibitzke and Robertson (1963) (see Cherry *et al.*, 1975) which show the effect of a group of high-permeability lenses in a low-permeability matrix, Brereton and Wilkinson had relied on a conceptual model of dispersion (Mercado, 1967) in a stratified aquifer in which each layer had a different hydraulic conductivity. On the subject of flow in fractured aquifers a Canadian hydrogeologist familiar with the fractured tills of the Prairies (e.g., Grisak *et al.*, 1976a) would feel very much at home with the fractured Chalk and Limestone and the Permo-Triassic sandstones which are the major British aquifers. In all three of these units the fracture permeability is greater than the intergranular, and the interior matrix acts as a chemical reservoir and pollutant sink.

If hydrogeologists are of the opinion that aquifers are sterile environments then the paper of J. F. MacNabb (EPA, Ada, Oklahoma) should give them cause for thought. To ensure microbial growth and function MacNabb pointed out the necessity of dissolved organic matter and other nutrients (e.g., N, S, P and inorganics), favourable oxidation-reduction conditions and sufficient electron acceptors (e.g., O_2, NO_3^-, SO_4^{2-}). He concluded from available information on these factors "that microbial activity is both possible and probable in most subsurface regions below the soil zone". He also noted that future developments in groundwater microbiology were dependent upon there first being significant advances in sampling and analytical methods.

MacNabb was challenged from the audience on the subject of the threshold Eh potentials for sulphate- and nitrate-reducing bacteria. Whereas MacNabb had quoted from the literature that sulphate reducers require an environment in which the Eh is less than -200 millivolts and that nitrate reduction by facultative microbes would not occur above 338 millivolts at a pH of 5.1, the field data presented in the following paper by W. M. Edmunds, as well as the experimental data of microbiologists suggest that these potentials are misleadingly low, particularly so in the case of sulphate reduction. MacNabb replied that such low redox potentials may occur in microenvironments in aquifers (e.g., in dead-end pores) and not necessarily throughout the aquifer. When the aquifer is pumped, however, both micro- and macro-environments would be sampled and misleadingly high redox values would be thus obtained.

In recent years there have been several review articles written on groundwater geochemistry but none have matched the insight given the subject by the paper W. M. Edmunds of the Institute of Geological Sciences, London. Edmunds began by pointing out that in the fissured aquifers of England (and the Prairies?) there may exist a compositional disequilibrium between the groundwater in the fissures (high permeability, low storage) and in the sediment matrix (low permeability, high storage). When a well is developed in such an aquifer, Edmunds suggested that the quality of the abstracted water gradually changes from the steady-state condition of the formation water to that represented by the mixing of induced-recharge and intergranular-storage waters.

Edmunds also noted that the size of most bacteria would deny them access to the intergranular matrices of the fine-grained Chalk and Limestone aquifers of the U.K., however they would be small enough to enter the pores of the Permo-Triassic sandstone aquifers and the fissures of all three aquifers. Until Canadian hydrogeologists obtain pore-size measurements on Canadian aquifer materials, we will be unable to draw such conclusions for our own aquifers.

Before launching into a detailed discussion of the geochemical controls of groundwater quality, Edmunds acknowledged the recent advances in both theoretical and analytical aqueous geochemistry - associating the theoretical advances with the works of Garrels and Christ (1965) and Stumm and Morgan (1970). He continued: "It is important that investigation of processes be undertaken with initial emphasis on field relationships; experimental and/or theoretical studies can only be meaningful if they relate to real situations in natural systems." Edmunds then proceeded to discuss the geochemical controls on groundwater quality in terms of geochemical abundance, solution-precipitation reactions, ionic strength and complex formation, acid-base reactions, redox reactions, ion exchange and surface reactions and membrane filtration. The discussion of each of the topics was illustrated with data taken from studies of British aquifers by Edmunds and his colleagues.

The second session ended with Professor Jacob Bear (Technicon, Israel) steering the assembled mass of mathematical philistines between the Scylla of integral calculus and the Charybdis of fluid mechanics so that all emerged with a surer knowledge of hydrodynamic dispersion.

Field Studies

The second day began with a discussion of field methods and results.

K. E. White of the Water Research Centre delivered an informative review of tracer methods for the determinations of groundwater residence times. In particular he pointed out that because of the halt in atmospheric testing of nuclear weapons the concentration of bomb tritium in the hydrosphere is now approaching natural levels. Consequently White suggested that consideration should be given to funding a crash programme of groundwater tritium measurement over the next five years so that groundwater ages in major existing and potential aquifers and waste management areas can be determined while bomb tritium is distinguishable from natural tritium and that arising from nuclear-power generation.

The problem of the magnitude of the dispersivity coefficient as a measure of the dispersive properties of an aquifer was reintroduced by Oakes and Edworthy (Water Research Centre). They had conducted a two-well tracer test of the Bunter sandstone at an artificial recharge site and had calculated a dispersivity of 0.6 m over a distance of six m. This is a value similar to that obtained by G. E. Grisak in alluvial gravels at Fort McLeod, Alberta and by J. F. Pickens in sands at Chalk River over similar distances this summer. As Oakes and Edworthy noted this value of dispersivity is approximately two orders-of-magnitude less than that determined by computer-simulation studies of a variety of hydrogeological environments in the USA (see the discussion by Cherry *et al.*, 1975, p. 80-81). The conflict in magnitudes between these types of dispersivity estimates will no doubt lead us to a profounder understanding of mass transport in groundwater flow systems.

A discussion on the causes of the increasing concentrations of nitrates in groundwater underlying arable land by Young and Hall (Water Research Centre) came to the same conclusion as that of Grisak *et al.* (1976b) at GAC Edmonton - that the ploughing of grassland releases large quantities of organically bound nitrogren which is subsequently oxidized to nitrate and then leached. Young and Hall are presently mathematically simulating the infiltration of nitrate, chloride and tritium through the unsaturated, fractured Chalk using both an intergranular seepage model and a model of fissure flow with ionic diffusion into the interstitial water.

Conclusion

In a short review such as this one cannot hope to do justice to all that was said and demonstrated over the course of three days. Consequently the interested reader is strongly urged to keep a weather eye out for the published proceedings which will also contain the papers presented at the sessions on simulation modelling and groundwater protection and rehabilitation.

The reviewer's comments have been limited to those papers which treated what appear to him as the major problems of and significant developments in contaminant hydrogeology - the measurement of the dispersion process, the microbiology of natural and contaminated groundwaters and the emergence of groundwater geochemistry as a distinct subdiscipline of both geochemistry and hydrogeology. However one theme recurred throughout the conference - that the key to our future progress lies in improving our laboratory and field methods of measurement, sampling and analysis.This point was made by both Keeley and MacNabb of the EPA; it is implicit in the quote taken from Edmunds' paper; and it is the driving force of the groundwater pollution program at the Water Research Centre. It is especially appropriate now that many of our mass transport simulation models have outstripped our capability to feed them the data they require to function in most operational situations.

From the broader historical perspective of the development of the sciences, it does seem that there now exist reasons for preferentially funding the development of measurement, sampling and analytical methodologies (e.g., for anaerobic bacteria, interstitial waters, groundwater velocity and aquifer dispersivity) rather than, say, mass transport simulation models (at least of the deterministic variety). Major conceptual advances in both marine chemistry (Horne, 1969) and biochemistry (Rose, 1966) occurred following a lengthy period during which the standard analytical and sampling methods for isolating and characterizing ionic and molecular species had been developed. Furthermore Hallam (1973) has argued that a crucial factor in the creation of the conceptual model of plate tectonics was the enormous body of advanced geophysical data that was collected following World War II, and which itself was made possible by advances in instrumentation and technique. It may well be that we have embarked on such a course in groundwater geochemistry (e.g., Edmunds and Bath, 1976). If so we can look forward with confidence to the development of improved conceptual models of the controls on groundwater quality.

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