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A SURVEY OF CONTAMINANT HYDROGEOLOGY IN CANADA

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Executive Summary

This paper was requested by the Editor for Hydrology of EOS, the Transactions of the American Geophysical Union. It describes the present state of research concerning ground-water pollution in Canada. In particular, it points out that, although there are relatively few hydrogeologists in Canada, there are numerous studies investigating the migration and fate of contaminants in the subsurface and that these studies enjoy international recognition.

Aperçu de l'hydrogéologie des contaminants au Canada

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Résumé

Cet article a été sollicité par l'éditeur de la section hydrologie d'EOS, la revue du American Geophysical Union. L'article fait le point sur l'avancement de la recherche sur la pollution de l'eau souterraine au Canada. Il y est question, notamment, de l'abondance d'études sur la migration et le sort ultime des contaminants dans le sous-sol, malgré le faible nombre d'hydrogéologues au Canada. Ces études ont un rayonnement international.

Aperçu de l'hydrogéologie des contaminants au Canada

Résumé

Dans les années soixante, les hydrogéologues canadiens se sont imposés par leurs études des grands réseaux souterrains des provinces de l'Ouest; l'actuelle génération s'imposera sans doute par ses études détaillées à des stations d'essais dont les dimensions se mesurent en mètres plutôt qu'en kilomètres. S'il existe une particularité de l'hydrogéologie actuelle au Canada, c'est bien le nombre d'expériences très bien définies à échelle réduite, axées sur l'étude de phénomènes hydrogéologiques, notamment la migration et le sort ultime des contaminants. Cet article tente de résumer cette activité et d'en montrer les origines.

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Abstract
While Canadian hydrogeologists in the 1960s made their mark by investigating the large ground-water flow systems of the Prairie Provinces, the present generation will likely be remembered for their detailed studies of test sites whose dimensions are measured in metres not kilometres. If there is any one phenomenon that is singular about Canadian hydrogeology in the mid-1980s it is the number of well-defined, small-scale research experiments devoted to the study of hydrogeological phenomena, in particular the migration and fate of contaminants. This article is an attempt to summarize that activity and its origins.

Introduction

At present there are about 250 hydrogeologists in Canada, a country larger than all 50 States of the Union but with a population only that of California. The relatively small number of Canadian hydrogeologists is partly due to the smallness of the research and regulatory agencies in the Federal and ten Provincial Governments, who between them employ fewer hydrogeologists than some USGS/WRD district offices, and partly to the lower Canadian use of ground water as a component of total water use (25% vs. 50+% in the USA).

Hydrogeology and/or ground-water hydrology is taught today at about 10 Canadian universities. The largest program is that at the University of Waterloo, 100 km west of Toronto, Ontario. Since its inception in 1971, the hydrogeology program at Waterloo has produced 140 graduates, of which 16 were Ph.D.s. Presently there are 50 in the graduate program, one third being Ph.D. candidates. There are active, but smaller, graduate programs at the universities of British Columbia, Alberta, Windsor, Toronto and Laval.

Writing 20 years ago, one of the founders of Canadian hydrogeology, Peter Meyboom (1966), observed that there existed two trends in hydrogeology. He referred to the first of these as the "inward look...directed at the very fundamentals of flow in porous media", generally conducted by laboratory experimentation. The second was "the outward look...aimed at large conceptions of groundwater flow", to which Meyboom himself had contributed through his studies of flow systems on the Prairies. He felt that ultimately these microscopic and macroscopic approaches would converge. This now seems to have occurred with the development of the numerous small-scale test sites spread across Canada, but concentrated in Ontario, which are dedicated to the study of hydrogeological phenomena in well characterized bodies of granular sediments or fractured rocks. That is, the test sites have become sufficiently well defined to allow field-scale experiments to be undertaken; in some cases, these field experiments have induced further laboratory experimentation.

Contaminant hydrogeology in granular media

Field-scale testing in contaminant hydrogeology grew rapidly in the late 1970s with test sites being developed at the Chalk River Nuclear Labs of Atomic Energy of Canada Ltd. (AECL), northwest of Ottawa, and at the Canadian Forces Base, Borden, north of Toronto.

Pickens and colleagues undertook several field tests at Chalk River using nonreactive and reactive tracers with the objective of determining the origin of the scale effect-- the large difference between laboratory column and field scale dispersivities first identified by Theis (1963). Pickens and Grisak (1981), then with the National Hydrology Research Institute (NHRI), ascribed this effect in the stratified outwash at Chalk River to aquifer heterogeneities and to the diluting effect produced by sampling from monitoring systems with large dead volumes. Pickens and colleagues (1981) also developed an injection-withdrawal test for determining the in-situ adsorption of a nonreactive tracer ^{85}Sr; the results of this test correlated well with the long-term behavior of ^{90}Sr elsewhere in the same aquifer. More recently, hydrogeologists with AECL (Killey and Moltanyer, Water Resources Research, in submission) have conducted extraordinarily detailed tracer tests in another area at Chalk River using vertical continuous profiles of tracer concentration (radioiodine) versus depth using 80 monitors and generating about 3/4 million data points.

While the Chalk River tests have been analysed assuming that the tracer spreading was due to advection and dispersion, the Waterloo group have used an advection-diffusion model to explain the observed tracer distribution in a similarly layered aquifer at Borden (e.g. Gillham and Cherry, 1982; Sudicky et al., 1983). In this model lateral advection causes the rapid migration of the tracer through the more permeable layers with transverse molecular diffusion causing interlayer tracer transport; the net effect is non-Fickian transport behavior (Gillham et al., 1984). These field observations were experimentally tested in a Plexiglass box containing a layer of sand sandwiched between two silt layers (Sudicky et al., 1985). They demonstrated that, in such media, the advection-diffusion model yields results that closely mimic the observed breakthough curves. However, in experiments with a reactive tracer there was increasing divergence between simulated and observed results as the transport velocity was decreased (Starr et al., 1985).

Borden has also been the site of two natural-gradient tracer tests studying the transport and transformation of organic contaminants. The first test was conducted jointly by Stanford University and the University of Waterloo and involved the injection of bromide, chloride and five halogenated organic compounds into the Borden aquifer and subsequent monitoring over a period of two years (Water Resources Research, in press). The second test was concerned with aromatic contaminants derived from refined petroleum -- benzene, xylene and toluene. For these compounds Patrick and Barker (1986) of the University of Waterloo determined retardation factors ranging from 1.1 (benzene) to 1.6 (m-xylene).

Retardation factors have also been determined by NHRI hydrogeologists (Patterson et al., 1985) for six organic compounds migrating in outwash materials at the Gloucester, Ontario landfill. At this site Whiffin and Bahr (1984) of GTC/Intera (Ottawa, Ontario) conducted a purge well test to determine the efficacy of decontaminating the aquifer by pumping. The test yielded both retardation factors and an estimate of the number of pore volumes to be purged to attain a specified level of decontamination (Jackson et al., 1985). Similar ground-water velocities were measured at the site by both a borehole dilution technique (Belanger, Ground Water, in submission) and the distribution of tritium in the aquifer (Michel et al., 1984).

Other studies concerning the migration and fate of organic contaminants are being undertaken at landfills throughout Canada. Barker of Waterloo and Reinhard of Stanford (Barker et al., 1986; Reinhard et al.,1984) have provided a particularly detailed account of the identity, quantitation and spatial distribution of organic contaminants migrating from the North Bay, Ontario landfill. Probably the largest plume of contaminated ground water in Canada is being purged from an outwash aquifer overlying fractured dolomite at Ville Mercier, south of Montreal; both units are contaminated with oil, PCBs and organic solvents (Poulin et al., 1985).

Complementing these studies of organic contaminant behavior are several concerned with the ground-water geochemistry of radionuclides. Johnston and Gillham (1984) were concerned with the effect of stable Sr concentrations on the measured distribution coefficient for radiostrontium. Others have measured the partitioning of ^{90}Sr in aquifer materials at waste disposal sites (Jackson and Inch, 1983; Lyon and Patterson, 1984; Johnston et al., 1985). Dubrovsky et al.(1984) investigated the acidification of a uranium tailings deposit at Elliot Lake, Ontario and accounted for the geochemical evolution of the tailings water. Killey et al.(1984) and Champ et al.(1984) studied the speciation of radionuclides in ground waters at Chalk River.

Finally, electromagnetic methods have become commonplace in the identification of polluted ground water, due to the work of Greenhouse at Waterloo (Greenhouse and Monier-Williams, 1985) and the Geological Survey of Canada (Stephens and Graham, 1985).

Contaminant hydrogeology in fractured media

Field testing of the hydraulic and transport properties of fractured media began in Canada in the mid-1970s with the work of Gale and others on bedrock in the Maritime Provinces and Cherry and others on tills in the Prairie Provinces. This led to the identification by Grisak and Pickens (1980) of matrix diffusion from fractures as a major sink for solutes in transport. (Its conceptual similarity to Waterloo's advection-diffusion concept in layered porous media reflects the role that Cherry and Grisak's work on Prairie tills have played in Canadian thinking.)

Recent work has concentrated on the statistical characterization of the fractured medium, the development of methods for measuring its hydraulic, transport and geochemical properties and the simulation of flow and transport, all of which have been prompted by the possibility that hazardous and radioactive waste disposal will take place in fractured rock.

Rouleau and Gale (1985) statistically characterized a fractured rock mass by detailed mapping of its fracture geometry, frequency and dimensions. Francis et al.(1985) identified the high permeability zones in a sandstone aquifer by hydraulic interference testing, geophysical logging and core inspection to establish hydraulic conductivity, anisotropy and fracture inter-connectivity. Bottomley et al. (1984) developed a borehole methodology to determine the geochemical properties of ground water in situ. Raven et al. (1985) instrumented a 200 m by 150 m by 50 m deep flow system in gneiss at CRNL and developed a fracture orientation-aperture model to describle flow and transport. Recent work by Gale et al.(1985) has shown that the cubic law, describing laminar flow in discrete fractures, may be invalid.

Novakowski et al. (1985) undertook an injection-withdrawal tracer test in similar rock nearby to determine dispersion within a single fracture. Feenstra et al. (1984) investigated the injection of wastes into a fractured sandstone. Schwartz et al. (1983) simulated macroscopic dispersion in a hypothetical fractured-rock flow system, concluding that dispersion in such systems is controlled by the geometry and interconnectivity of the fracture network. Hitchon et al. (1985) have simulated flow and aquifer response in a deep sandstone in the Western Canada sedimentary basin to determine its suitability for liquid waste injection.

Concluding Remarks

Contaminant hydrogeology has developed rapidly in Canada during the present decade and has won international recognition. In 1984 Les Smith of the University of British Columbia and Frank Schwartz of the University of Alberta shared the GSA's Meinzer Medal for their work on the simulation of contaminant transport. In 1985 John Cherry of the University of Waterloo won both the Meinzer Medal and the AGU's Horton Medal for his contributions to the field. What better justification for a Canadian team

(Schwartz et al.,1985) to be the first to attempt the development of an expert system for contaminant hydrogeology!

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