How Hydrogeology Can Save the World

An Editorial submitted to *Ground Water*

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I have read with interest recent editorials and articles in *Ground Water* discussing the future of hydrogeological research. Is it the beginning of the end, or is it simply time for a shift in focus? What can we infer from citation trends, or from a move toward more practical applications? These questions lead to interesting debates. Definitive resolution of these debates is unlikely. However, there does appear to be a sense in the community that new directions, with applications that address truly important problems, are needed to revitalize hydrogeological research.

While ground-water contamination was a highly visible and important environmental concern for much of the 1980's and early 1990's, this concern has faded considerably, and the current problems that dominate the broad environmental landscape are carbon dioxide, greenhouse gas emissions, and global warming. A recent editorial in Ground Water discussed how ground-water resources, and the field of hydrogeology, might be impacted by global warming. While this type of passive role needs to be planned for, I submit that hydrogeology may have a central, active role to play in solving the CO_2 problem, and that CO_2 sequestration represents a new and potentially important problem area for hydrogeololgic research.

What does hydrogeology have to do with greenhouse gas emissions? Well, the reality is that there is very little chance for a significant shift away from fossil fuels over at least the next several decades. Therefore any solutions to the CO_2 problem will require active human intervention in the fossil fuel utilization cycle and/or additional intervention in the global carbon cycle. Because CO_2 is a by-product of fossil fuel utilization, active management of the CO_2 in waste streams is required if the build-up of atmospheric CO_2 is to be mitigated.

A wide range of options is being considered to actively manage CO_2. Relatively low-cost options include planting more trees (terrestrial biological sequestration) and fertilizing the oceans to increase ocean uptake of CO_2 (marine biological sequestration). These options use minimal human intervention, and focus on increasing natural uptake processes. Estimates of added storage capacity associated with forestation indicate minimal effects on global CO_2, and ocean fertilization has met with disappointing results to date.

More active interventions involve capture of the CO_2 before it enters the atmosphere, and storage or disposal of the CO_2 in ways that prevent its return to the atmosphere. Capture technologies are a challenge, and ongoing research is producing promising results. However, I will not discuss these technologies here. Possible storage or disposal methods include injection into deep oceans and injection into deep geologic formations. Deep-ocean injection faces strong resistance from environmental groups, and is unlikely to emerge as an important option for CO_2 storage. Deep geologic injection is emerging as the most promising option for CO_2 disposal. Of the three major types of formations being considered - depleted oil reservoirs, unminable coal seams, and deep saline aquifers - deep aquifers are seen as the most promising because of their large capacity and widespread availability.

In order to take advantage of increased CO_2 density, and associated reductions in volume needed for storage, most proposed strategies involve injection of CO_2 in a supercritical state, such that pressure exceeds 7.38 MPa and temperature exceeds 31.1^{o}C. Therefore injection would take place at least 800 meters below land surface. At these depths, formation waters have high amounts of dissolved solids, and are seen as having little or no economic or ecological value. Therefore these are attractive targets for CO_2 injection. Experience in the petroleum industry involving CO_2 injection for enhanced oil recovery, and in the hydrogeology industry involving deep injection of hazardous waste, provide a strong base from which to analyze CO_2 injection into deep aquifers. However, while each of these activities is similar to CO_2 injection into deep aquifers, unique problems associated with proposed CO_2 injection schemes make the problem an interesting research challenge. These include high degrees of uncertainty in formation properties, buoyancy and viscous effects that can lead to complicated, unstable flow patterns, phase changes in any CO_2 that leaks from the target formation and flows vertically upward, complex geochemistry, and long time scales over which the CO_2 transport must be analyzed.

While the problem is challenging, many of the salient features are familiar to hydrogeologists. These include regional flow systems with layered aquifer/aquitard units, local- and intermediate-scale heterogeneities, two-phase flow, inter-phase mass transfer and associated miscible transport, phase change with significant changes in phase properties, and complex geochemical reactions. While economics is an important consideration, public acceptance depends on credible estimates of the ultimate fate of the injected CO_2, and associated environmental risk management. Hydrogeologists have spent the last three decades or more dealing with these issues, and are ideally positioned to contribute vital research to determine the suitability of this proposed solution to the global warming problem. If this technological solution is to succeed, hydrogeology must provide environmental assurances and make credible assessments of environmental risks. In this way, hydrogeology can help to save the world from global warming, while working in a new and revitalizing area of research.