For over three decades, my hydrogeologic career has blended basic science coupled with providing my expertise to private and governmental entities that need to expeditiously answer questions on water supply, wetland, or contaminant problems. In the process, I discovered that much of what I used to teach in my basic hydrogeology courses, including rigorous mathematical and geochemical tools, could not be used by my students once they left ‘the fold’ unless they became professors who also do basic research.

This is because consulting hydrogeologists and engineers usually collect only scant or incomplete data to solve problems, compared to what is collected by academics or United States Geological Survey (USGS) scientists. Regulatory protocols, cost, and the inability of non-hydrogeologists to understand what is done constrain the kinds of analyses done in the ‘real world’. By scant and incomplete data, I mean the installation of fewer than a dozen monitoring wells in a football-field-size contaminated site, drilling only two or three test holes for a water supply system, and not collecting analytical data on major dissolved solids and oxygen content of sampled waters.

As a consequence of data limitations outside of academia and the USGS, I have become increasingly reductionist in my philosophy on how hydrogeology should be both taught and practised (Siegel, 1999, 2006). Although the sophisticated tools available to hydrogeologists often cannot be used properly in practice, the fundamental concepts underlying the science remain valuable in figuring out what one can do with scant data, and how to efficiently collect data that will be most useful.

I write this essay to present my ‘top ten’ list of what students and practising hydrogeologists fundamentally need to know to be successful—the ten points I want my students to remember even 10 years after they graduate.

Don Siegel’s ‘Top Ten’ List

1. ‘The Hydrogeologist’s Credo’ (paraphrased from Aristotle) needs to be followed

‘Don’t push the data farther than they can be pushed and be honest with respect to what can be done’. Too often, for example, practitioners tell clients that numerical models can forecast contaminant transport and remediation success when there are few, if any, concrete examples, showing that this can be done for typical contaminant sites that have scant data (Siegel and Otz, 2007).

Why? Hydraulic conductivity measurements, at best, are only valid to a few factors to an order of magnitude because of scale dependency (e.g. Schulze–Makuch et al., 1991) as well as experimental design. Pushing analysis beyond this error bar provides no better understanding of the problems being addressed. Furthermore, preferential zones of high permeability refract flow lines both horizontally and vertically, and often there are insufficient monitoring wells to evaluate if groundwater actually moves in the direction of maximum hydraulic gradient (e.g. McDonnell et al., 2007; Otz and Azzolina, 2007). Moreover, the time frame during which we acquire data is usually short compared to the forecasts we have to make.
Some argue that using random hydraulic conductivity distributions derived from scant data bases provides mathematical ‘certainty’ that professional judgement does not (e.g. Neuman and Wierenga, 2003; Neuman, 2007). However, under circumstances of scant data, many hydrogeologic conceptual and mathematical models fail because of ‘surprises’ unanticipated during the analysis, including errors in assumed distributions of hydraulic conductivity (e.g. Bredehoft, 2004).

Fundamentally, I think practising hydrogeology, similar to practising its close cousin, petroleum geology, constitutes as much of an art as a science, and that the ‘meta data’ of experience leads to more success than sophisticated attempts at analysis, unwarranted by the field data and is difficult to explain to the non-specialists who make the regulatory and financial decisions regarding the groundwater problem being investigated.

2. Darcy’s law needs to be understood at the ‘gut’ level
Changing hydraulic gradients on hydrogeologic cross sections, water-table maps, and potentiometric surface maps implies changes in some combination of discharge, cross sectional saturated area, or hydraulic conductivity. Figuring out why hydraulic gradients change leads to important inference on unknown sub-surface geology and hydraulic properties. With respect to Darcy’s Law, the difference between seepage and Darcy velocity needs to be so well known that it becomes second nature—the former calculates how fast groundwater moves and the latter how much moves across a unit cross-sectional area.

3. Potentiometric surfaces are different from the water table
Too often, I have seen practitioners mix water-level data from piezometers and water-table monitoring wells in preparing maps. Water levels in monitoring wells and piezometers measure the hydraulic potential energy of the water where it enters the screen of the well, much like old thermometers measure temperature (thermal energy) by how high mercury rises in the stem. This concept, which encompasses the reason why water levels in nested piezometers at the same place may be different. Why the water table is different from a potentiometric surface is the most difficult fluid mechanics concept for students to understand. They need to understand it cold.

4. Surface water is an ‘outcrop’ of the water table
Groundwater connects to surface water. Hydrogeologists need to know that the way water-tables contour ‘V’ when they cross streams defines assumed or known groundwater—surface-water connections. They also need to know how to directly measure recharge and discharge at lakes, streams, and wetlands (see Winter et al., 1998, for an outstanding review).

When I ask consulting hydrogeologists what they would like professors to emphasize more in their hydrogeologic courses, they often say groundwater and surface-water interaction. I have seen many water-table maps that had contours crossing lakes (impossible unless the lake surface is tipped!) and showed groundwater unrelated to streams when the consulting report said groundwater supported stream base flow.

5. Groundwater occurs in nested flow systems, separated by hydraulic boundaries
This concept, first presented in detail by Toth (1963) and then expanded by Freeze and Witherspoon (1967), underpins our understanding of hydrogeologic systems at many scales. But students should also realize, that multiple-flow systems do not develop in highly permeable systems, compared to those in less permeable or layered geologic materials (e.g. Haitjema and Mitchell–Bruker, 2005), and that nested-flow systems may not always occur at the scale of the problem being looked at.

6. Groundwater chemistry is predictable from first principles
If I can, I always obtain concentrations of the major solutes (calcium, magnesium, sodium, bicarbonate, sulfate, and chloride) from groundwater samples collected by either low flow pumping or filtered after sampling. This is so that I can evaluate the accuracy of the laboratory by the charge balance method and to make sense out of the chemistry—something that often cannot be done using ‘total’ solute analyses that incorporate suspended particulate matter with the solutes. Ironically, regulatory quality assurance protocols do not insure quality data from a scientific standpoint for many solutes.

Most of all, the major chemical compositions of natural and many contaminated groundwaters are predictable from common reactive minerals and/or waste (Piper, 1944; Back, 1960). If what is observed does not fit the hypothesized chemistry, then reasons need to be explored. In the absence of full analyses, I look at what geochemical data I have within the context of what I would expect given the waste stream or aquifer mineralogy.

7. Chemical oxidation and reduction control many important groundwater and contaminant chemical compositions
The water pH and oxygen content largely dictate what happens geochemically in groundwater systems beyond dilution and mixing. Most organic matter strips out dissolved oxygen, mobilizes many trace metals, and leads to the biodegradation of many contaminants (e.g. chlorinated solvents). Information on both
pH and oxidation state of water is needed to address almost any water quality problem, even qualitatively, by inference from dissolved solute species present (e.g. Berner, 1981). Dissolved oxygen content of groundwater can always be taken in the field. It is a trivial measurement with inexpensive field kits now available, and provides critical information on groundwater chemistry, and contaminant mobility and transformations (e.g. McMahon and Chapelle, 2008).

8. As a working approximation, contaminant plumes should be considered narrow and no wider than a few times the width of the source at their heads
Contaminant issues remain the ‘bread and butter’ of applied hydrogeology. ‘Amoeba-like’ or very wide plumes suggest multiple contaminant sources, preferential flow paths, changing seasonal water table configurations, bad data, or bad contouring. Plumes can also plunge below the water table and extend farther than anticipated from scant monitoring of well data (Simmons et al., 2001). In the case of contamination issues, theory ‘trumps’ data sets which suggest outlandish transport conditions unless they can be proved.

9. Contour using your head, and not your computer
Several years ago, I visited the famous Exxon Mobil labs in Houston. There I saw petroleum geologists contour thickness and elevation data and then digitize the contours. I asked why they did not have computer programs do the contouring for them. Their answer—computers do not know geology. The same principle applies to hydrogeology. Contouring scant data by hand leads to thinking about what happens in the sub-surface, and avoids making regrettable mistakes regarding groundwater—surface-water interaction and assumed lateral boundaries conditions to the flow system. If contouring programs have to be used (I know of one regulatory agency that forces them on scientists and engineers to ‘avoid subjectivity’), then how these programs interpolate and extrapolate should be carefully investigated to avoid gross interpretive errors, forced by scant data distributions. Sometimes, ‘fake’ data will have to be inserted hidden in the data field to force contours to scientifically reasonable configurations.

10. Explore simple bivariate plots as an analysis tool
I successfully use bivariate plots (X vs Y) all the time to determine where mixtures of water occur, investigate fingerprint contamination, determine whether contaminants or other solutes are naturally removed along flow paths, and evaluate recharge and discharge relationships from water level data, to name only a few applications. Bivariate plots, when used creatively can provide insight in a manner that even lay people can understand.

But in all cases, I use bivariate plotting to test hypotheses on what happens geochemically or hydrologically—never as a purely empirical tool with which I search for possible relationships. I always use the scientific method in my application-based hydrogeology, just like when I study basic research questions.

Now that I have presented my ‘top ten,’ I look forward to seeing what differences, additions, or subtractions colleagues may have.

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