American Petroleum Institute

API SOIL & GROUNDWATER RESEARCH BULLETIN

A summary of research results from API's Soil and Groundwater Technical Task Force.

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Estimation of Infiltration and Recharge for Environmental Site Assessment

An accurate estimate of the rate that water infiltrates downward through a contaminated soil (i.e., diffuse recharge) is essential for quantifying the threat to an underlying aquifer. Results from Risk-Based Corrective Action (RBCA) analyses and contaminant fate and transport models (e.g., EPA's EPACMTP and API's VADSAT) are very sensitive to the infiltration or recharge rate value selected by the analyst.

The American Petroleum Institute (API) reviewed the scientific literature for published recharge data and examined existing methods for obtaining recharge estimates. The specific objectives of this study were to (1) summarize the key concepts and soil physics principles related to diffuse recharge; (2) describe, compare, and contrast estimation techniques for assessing petroleum hydrocarbon or salt-impacted sites; (3) compile site-specific recharge estimates from sites throughout the country; and (4) identify areas for further research. This bulletin summarizes the results of the study documented in API Publication 4643, "Estimation of Infiltration and Recharge for Environmental Site Assessment."

APPLICABILITY OF RECHARGE ESTIMATION TECHNIQUES

A literature search revealed dozens of methods, both physical and chemical, to quantify diffuse recharge in humid and dry climates. For determining site-specific recharge estimates, techniques that rely on very local measurements are most appropriate. Such techniques include lysimeters, chemical tracers, the Darcy flux and plane of zero flux methods, one dimensional soil-water balances and soil water models, and soil temperature methods based on near-surface soil temperature gradients.

Soil lysimeters are the most accurate (and often most costly) approach to estimating recharge in any climate. These devices collect deep percolating soil water that eventually would reach the water table.

In humid climates, reasonably accurate recharge rates can be obtained from water balance calculations in the vadose zone, provided that the period of accounting is weekly or more frequently. Vadose zone chemical tracers may provide more accurate estimates in dry climates for low to moderate cost.

SUMMARY OF RECHARGE ESTIMATES

API gathered diffuse recharge estimates from the open literature and through requests for information from U.S. Geological Survey district offices throughout the country. These data were compiled to (1) identify key studies and sources of information on recharge estimates throughout the U.S., (2) understand which techniques are being applied in various hydrogeologic and climatic settings, (3) determine the frequency with which the various techniques are being applied, and (4) develop a database for future statistical analysis.

The recharge estimates were tabulated for watersheds throughout the country. Information recorded for each recharge study area includes climatological data, site physiography, and general soil characteristics. The recharge estimates are organized according to major surface drainage basins within geographic regions and estimation technique. A copy of the database is included in API publication 4643, "Estimation of Infiltration and Recharge for Environmental Site Assessment."

The recharge estimates in the API database were derived primarily from soil-water balance techniques and stream flow analyses. In addition, examination of the data reveals that within any climatic region, individual studies produce a wide variation in the recharge estimates. This variation may be attributed to differences in the scales of investigations.
(i.e., Studies conducted over large vs. small land areas.)

METHODS TO QUANTIFY DIFFUSE NATURAL RECHARGE

Physical methods include both direct and indirect techniques. The only direct method of measuring recharge is lysimetry, which is costly relative to the other techniques and requires lengthy data collection periods. Indirect methods described in this report include:

- Soil-water balance
- Darcy flux
- Plane of zero flux
- Soil temperature
- Electromagnetic
- Groundwater basin outflow
- Water-level fluctuation
- Stream gauging

The soil-water balance method is one of the most widely used indirect estimation techniques. However, the accuracy of this method depends upon the accuracy of estimates of its component parameters (runoff, infiltration, evapotranspiration and storage), which sometimes are poorly known or exhibit significant variability at a site. The greatest uncertainty lies in estimating evapotranspiration. API found that recharge estimates using the soil-water balance method can vary over two orders of magnitude over large areas. However, this method may be suitable for small sites in humid or temperate regions where parameters that rely on climatic data are known to have low variability. Several vadose zone field test methods and equations needed to measure or calculate the component parameters of the water balance equation are reported in API Publication 4643.

The Darcy flux and plane of zero flux methods provide useful estimates when resources are available to collect a sufficient number of field measurements. These methods require measurements of vadose zone moisture content and hydraulic conductivity over the seasonal range of site-specific soil moisture conditions.

The soil temperature, electromagnetic, groundwater basin outflow, water-level fluctuation, and streamflow methods provide regionally averaged estimates of diffuse recharge. These methods may be most useful when the regional hydrogeology (i.e., the location of recharge areas and aquifer boundaries, storage and outflows, etc.) is well understood.

Chemical methods for estimating diffuse recharge are subdivided into those requiring measurements in either the vadose or saturated zones. Where project resources permit, chemical methods may provide better estimates of long-term recharge because they reflect recharge conditions over long periods of time.

Vadose zone, chemical tracer methods track the movement of stable and radioactive isotopes. Chemical methods include the chloride mass balance method and those method using tritium, chlorine-36, and stable isotopes as tracers. Chemical tracer techniques in the saturated zone determine the age of groundwater, which in turn permits calculation of groundwater travel time. Where recharge to an aquifer occurs primarily by direct local recharge, the age of the groundwater is related to local recharge. Chemical tracers used in aquifers include tritium, chlorofluorocarbons, krypton-85, carbon-14, and chlorine-36.

Mathematical models (soil-water and groundwater) are best suited to predict recharge when the physical properties of the soil and groundwater are well characterized. The water balance models typically require site-specific climatic data for precipitation, temperature and solar radiation; soil characteristics data including porosity and moisture retention characteristics; or a limited set of soil characteristics parameters, including field capacity, wilting point, saturated moisture content, and organic matter content.

The soil-water balance model HELP (Schroeder *et al*., 1994) was reviewed as a tool for estimating recharge rate. If recharge rates are low and the period of soil-water balance accounting is too long, then HELP (and other soil-water balance models) are likely to underestimate recharge because they only roughly approximate the physics of unsaturated flow. However, at one arid-climate field site, examined for the API study, HELP-generated recharge estimates compared favorably to independent estimates using the Darcy flux method and the chloride mass balance technique.

CHOOSING AN APPROPRIATE RECHARGE ESTIMATION TECHNIQUE

No universally acceptable methods to compute diffuse recharge can be applied to all sites. The method selected will depend on the site geology, soil characteristics, depth to the water table, vegetative cover, and climatic conditions, along with factors such as time constraints, available budget, and the importance of the recharge estimate to the success of the project. Table 1 compares the data requirements, optimal site characteristics for application, relative accuracy and relative cost for the each of the methods examined.

TABLE 1. COMPARISON OF METHODS FOR ESTIMATION OF DIFFUSE RECHARGE

Estimation Technique	Data Requirements	Optimal Site Characteristics	Relative Accuracy[1]	Relative Cost[2]	Comments
Soil-water balance	• Precipitation (P) • Surface runoff • Evaporation (E) • Transpiration (T) • Storage (S)	Humid/temperate climate (P≥ET); flat topography with measurable or negligible runoff; short, uniform vegetation; small scale	Low	High/low	Commonly used technique, not appropriate for arid climates where ET>>P; uncertainty varies by a factor of 3 to 10 or more. High cost if micrometeorological equipment pre-purchased; low if ET is calculated from PET.
Lysimetry	• Water volume	Applied under any site conditions; construction results in devegetation	High	High	Direct, precise measurement of deep drainage; precision ±1 mm/yr; long-term monitoring and maintenance required; when combined with soil-water balance, is very reliable for arid site
Darcy flux	• Hydraulic gradient Unsaturated hydraulic conductivity	Applied under any site conditions	Low to moderate	Low to moderate	Results rely on measurement of unsaturated hydraulic conductivity; accurate with ± a factor of 10 or more
Plane of zero flux	• Soil water potential profile • Water content changes with time	Temperate, semiarid, or arid climates (ET>P); any soil type	Moderate	Moderate to high	Accuracy ±15% or ~20 mm/yr; requires weekly monitoring; fails during periods when rainfall exceeds K_{sat}
Soil temperature gradient [Bredehoeft and Papadopulos (1965) type-curve method]	• Steady-state temperature profile data from saturated zone	Deep aquifers with upward temperature gradient	Low	Low	Provides regionally averaged recharge estimate with accuracy similar to basin water balance
Electromagnetic resistivity	• Electrical conductivity measurements • Independent recharge estimate for comparison	Fine-grained soils; varied vegetation and climate	Non-quantitative	Low to moderate	Provides reconnaissance-level, qualitative results that identify areas of recharge
Basin outflow	• Aquifer transmissivity • Aquifer hydraulic gradient basin boundaries • up stream watershed surface area • Specific yield • Transient hydraulic head change	Any unconfined aquifer with a well-characterized flow regime, and well-defined recharge areas	Low	Low to high	Provides regionally averaged recharge estimate with accuracy similar to basin water balance; can often rely on existing data. Low cost provided data already exist; high cost if data collection required.
Water-level fluctuations	• Water table hydrograph • Specific yield	Any unconfined aquifer with a well-characterized flow regime, and well-defined recharge areas	Low	Low	Provides regionally averaged recharge estimate with accuracy similar to basin water balance; can often rely on existing data
Stream gauging	• Streamflow hydrograph	Humid/temperate climate; well-developed, unmanaged watershed with perennial streams; stream-connected shallow aquifer; minimal snowmelt	Moderate	Low	Avoids need to measure climatic parameters; provides regionally averaged recharge estimate for watershed with better accuracy than basin water balance
Tritium profile	• Undisturbed soil profile below the root zone • ^{3}H input function • ^{3}H concentrations in soil moisture	Arid, semiarid and temperate climates where R>10% MAP; sediments of any texture and pedogenic carbonates	High	Low	Very accurate water tracer; conceptual model assumes piston flow (i.e., ignores preferential flow); subject to vapor transport, which causes overestimate of R where R ≤ 1 mm/yr
Chlorine-36 profile	• Undisturbed soil profile below the root zone • ^{36}Cl input function • ^{36}Cl concentrations in soil moisture	Arid, semiarid and temperate climates where R>10% MAP; sediments of any texture and pedogenic carbonates	High	Low to moderate	Fairly accurate water tracer, subject to anion exclusion and ultrafiltration; conceptual model assumes piston flow (i.e., ignores preferential flow); high cost of analysis ($500-$1000/sample)
Chloride mass balance	• Undisturbed soil profile • Meteoric chloride concentration • Chloride concentration in soil moisture • Mean annual precipitation	Arid, semiarid and temperate climates where R>10% MAP; sediments of any texture and pedogenic carbonates	High	Low	Conceptual model assumes (1) average rate of chloride deposition in precipitation is constant, and (2) piston flow; very inexpensive
Stable isotope profile	• Undisturbed soil profile • Water content profile • D and ^{18}O concentrations in soil moisture	Arid and semiarid climates where soil-water movement is in quasi-steady-state; sediments of any texture	Unknown	Low to moderate	Conceptual model assumes one-dimensional, vertical, quasi-steady-state soil-water movement; non-routine soil-water extraction process; requires further research to evaluate uncertainty
Ground-water age dating	• Hydraulic gradient • Effective porosity • Distance to tracer peak • Apparent ground-water tracer age	Shallow, unconfined aquifer; vertical hydraulic gradients near the water table; applicable to any climate, soil texture and vegetation	High	Low	Ground-water age best determined by $^{3}H/^{3}He$, ^{36}Cl, and/or CFCs; requires thorough understanding of aquifer flow system and careful application; very consistent results. High relative accuracy if source of ^{3}H is known.
Soil-water balance models	• Precipitation • Surface runoff • Evapotranspiration • Soil-water storage • oil hydraulic properties	Applicable to any conditions and any scale where vertical flow occurs	Low to moderate	Moderate to high	Relies on estimates of AET and unsaturated hydraulic conductivity; uncertainty varies by an order of magnitude or more
Soil-water models based on Richard's equation	• Climatic data • Soil hydraulic properties • Depth to water table • In Situ pressure head or water contents	Homogeneous soil profiles above a shallow water table; moist soils	Low to moderate	Moderate to high	Uncertainty is due to climatic data and hydraulic properties. Extensive computational effort for deep water tables, dry heterogeneous soil.
Ground-water models	• Aquifer geometry • T ransmissivity, storage • Aquifer boundary conditions • Initial head field	Applicable to any conditions and any scale	Moderate	Moderate to high	Cost can be considerable if data are not compiled. Requires thorough calibration.

[1] Relative accuracy is a qualitative comparison of the accuracy of the method when applied under optimal site conditions and, like the relative cost tabulation, is based on professional judgment and experience.

[2] Relative cost is based on the past experience of the authors of API Publication 4643 and the following criteria: low cost: less that $10,000; moderate cost: $10,000; to $50,000; high cost: greater than $50,000.

In most cases, a limited project budget dictates the use of a less sophisticated technique. In such cases, one must accept some uncertainty in a site-specific recharge estimate and must attempt to understand the degree of that uncertainty. However, no comprehensive uncertainty analysis exists for the techniques examined.

When time and budget are limited, one may refer to estimates contained in reports by the U.S. Geological Survey or state and local water resource or geological surveys. Where site-specific measurements are required but resources are limited, one may consider an approach using a one-time data collection such as a Darcy flux analysis based on laboratory or field measurements of the deep vadose zone hydraulic properties or chemical tracer sampling of the vadose zone. If resources are available, it is desirable to use both a physical and chemical method.

FUTURE RESEARCH

This study revealed several areas in which further research is needed, as outlined below:

- The reliability of some of the key methods to quantify recharge, especially in dry climates, needs to be improved. One example where considerable improvement could be achieved is in critically evaluating assumptions in the widely used chloride mass balance method.

- Methods are needed to rapidly address the nature of spatial variability in recharge over large areas. In particular, methods for quantifying the contribution of flow through macropores are needed.

- A better understanding of recharge method uncertainty in various hydrogeologic and climatic settings is needed. Additional comparison studies of the low-cost, simpler estimation techniques with more rigorous measurement systems, under a variety of conditions, would provide useful uncertainty data on recharge estimates used in risk-based corrective action and other site-modeling efforts.

- Further statistical analysis of the database compiled in this study may reveal a useful correlation between precipitation and recharge for various physiographic provinces and climatic regions.

ABOUT API'S SOIL & GROUNDWATER TECHNICAL TASK FORCE...

API's Soil and Groundwater Technical Task Force provides an expert, multidisciplinary technical focal point within API to address soil and groundwater issues. The Task Force identifies and defines emerging technical issues related to soil and groundwater contamination/protection, and develops research programs to address these issues. API-sponsored research yields practical tools and basic science for risk-based, cost-effective solutions to the petroleum industry's soil and groundwater problems. The Task Force disseminates information and research results through publications, presentations, and interaction with industry clients and regulatory agencies.

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