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Quantifying Return Flow to Groundwater: What's in the Tool Box?

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What's in the Tool Box

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Introduction

Return flow to groundwater is the quantity of water applied at or near the land surface which infiltrates back (returns) to the groundwater system. Common uses that lead to return flow are irrigation of agricultural fields, golf courses or lawns, domestic wastewater disposal through septic systems, and artificial recharge. Quantifying the amount of this applied water that percolates to the water table is necessary in many water-short western states to prove beneficial use, evaluate return flow credits, demonstrate the portion of a water right which can be transferred to another party, and for water banking computations in aquifer storage and recovery projects. Return flow analysis is also relevant to municipal water reuse projects, where the impacts to groundwater quality from landscape and golf course irrigation or artificial recharge with treated wastewater are a potential concern.

The purpose of this paper is to describe return flow processes and methods available to quantify return flow to groundwater. The first part of the paper sets the statutory and regulatory contexts for return flow analyses. The second part of the paper deals with a review of the available methods to quantify return flow to groundwater. Although a very common method is the water balance approach applied at the point of use, with the corresponding assumption that the residual water component becomes deep percolation (return flow), we emphasize the less commonly used approaches that rely on data and computations in the vadose zone and in the aquifer.

Statutory and Regulatory Context

The quantity of return flow to groundwater influences several types of water rights decisions, including allowable diversions for permitted water rights, potential impairment of surrounding wells, and impacts to streams from new groundwater pumping. Where groundwater resources management decisions are based on determination of annual water budgets, accurate quantification of return flows will affect decision making. In critical management areas, where groundwater resources management decisions are based on determination of annual water level declines, demonstrating return flow to groundwater will reduce the magnitude of projected water level declines that would otherwise be associated with a specific application. Therefore, the estimated volume of return flow can impact whether a particular application will be approved and, if approved, how it will be conditioned.

Methods of Quantifying Return Flow

A wide range of methods are available to quantify return flow to groundwater (Figure 1).
In most cases, the method chosen will depend largely on the statutory and regulatory context as defined by state and local policies. Other factors that influence the selection of a method to quantify return flow to groundwater include (1) the nature and complexity of the hydrogeologic

system, (2) the current understanding of the hydrogeologic system, and (3) the amount of time and money available to characterize the processes of interest.

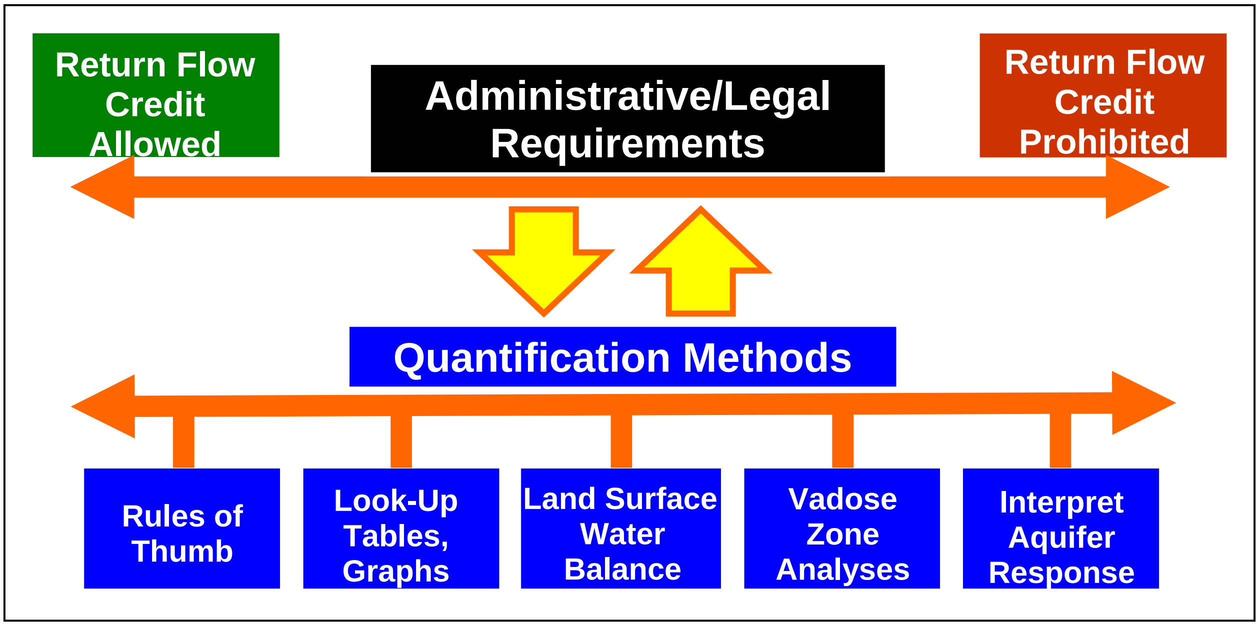

Figure 1. Methods of quantification available to quantify return flow to groundwater and factors influencing method selection.

Rules of Thumb, Look-Up Tables, and Empirical Equations

Rules of thumb include the generally accepted rules or conventional wisdom that has been adopted by regulatory agencies. These rules of thumb are often adopted for the sake of simplifying a complicated regulatory issue, and in many cases, rely on the implicit assumption that every system in question behaves in a similar manner. Often, there is little, if any, scientifically defensible justification supporting these rules of thumb. Some of the rules of thumb are based on inappropriate assumptions about the nature of water movement in the vadose zone.

"Many water managers assume that about half of the water diverted from a stream may return over some period of time....a few scientifically defensible studies show that return flows may range from 60 percent of the diverted flow to zero (no return)." (Wyoming Game and Fish 2002).

In some cases, rules of thumb provide the baseline regulations defining the amount of return flow credit that can be granted for certain practices; applicants have the option to request a larger credit if they can provide evidence supporting the validity of their request. For example, the Colorado Office of the State Engineer states that municipalities can apply for an irrigation (turf grass) return flow credit of 15% of the water applied; if the municipality requests a greater credit, documented reports are required to validate the request (Oad and DiSpigno 1996).

Look-up tables and empirical equations generally provide more flexibility than rules of thumb. Look-up tables and empirical equations are based on previous investigations which have characterized deep percolation as a function of various factors, such as the type of water application (sprinkler, drip, or surface irrigation), vegetation type, and volume of irrigation water applied. For example, graphs of deep percolation as a function of total water application were derived from lysimetry data for turf grass near Denver and Colorado Springs (Oad and DiSpigno 1996).

Soil-Water Balance Residual

One of the more common methods of quantifying return flow to groundwater is the soil-water balance method. The soil-water balance (Figure 2) is applied at land surface, and the residual component is assigned to deep percolation. The accuracy of deep percolation is a function of the accuracy of each component of the soil-water balance. In the arid southwestern United States, evapotranspiration (ET) is the component with the largest uncertainty. Reducing the uncertainty in ET, therefore, can significantly improve estimates of deep percolation. Many methods of measuring ET are available, including micrometeorological methods (i.e., the Bowen Ratio Method, the Eddy Correlation Energy Balance Method, and the Penman Monteith Equation), reference tables, and remote sensing methods (e.g., Allen 2003).

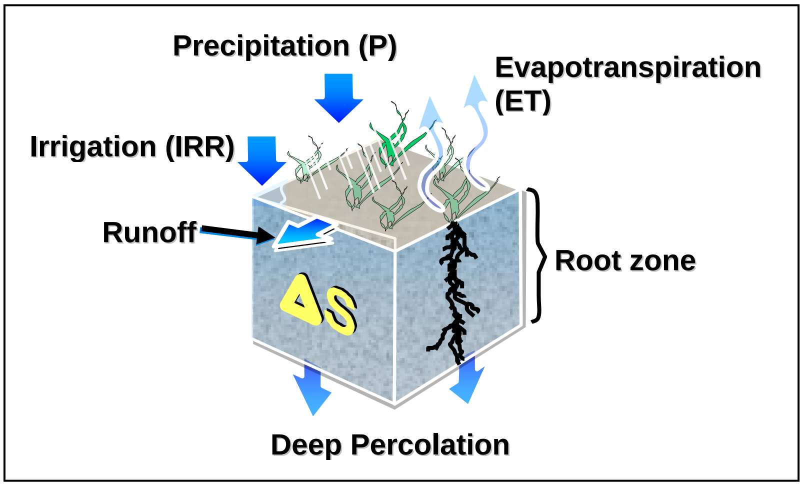

Figure 2. Components of the soil-water balance.

Vadose Zone and Groundwater Analyses of Deep Percolation

Many methods for quantifying return flow to groundwater rely on analyses of data collected from the vadose zone. These methods include calculation of the Darcian flux, application of soil temperature to estimate the downward flux of water, application of geochemical tracers, and unsaturated flow models. These methods rely on data collected at the specific site of interest.

One of the most direct methods of estimating deep percolation is to calculate the Darcian flux, which requires measurements of unsaturated hydraulic conductivity, soil water potential and hydraulic gradient. The unsaturated hydraulic conductivity can be calculated from a moisture retention curve (e.g., Millington and Quirk method; van Genuchten method), can be estimated using grain size data (e.g., Rosetta), can be measured in the laboratory (e.g., one-step outflow method) or in the field (e.g., instantaneous profile method, tension infiltrometer). The hydraulic gradient is determined from measurements of soil water potential (e.g., tensiometer measurements) or by assuming a gravity flow (vertical hydraulic gradient = 1).

Interpretation of soil temperature profiles is another method of estimating deep percolation rates. Soil temperature can be easily and accurately measured using thermocouples or thermistors. The temperature profiles can then be interpreted by one of several methods, including the type curve (Sammis et al. 1982) or analytical method (Stallman 1963) for steady state profiles or the temperature change method for transient profiles (Taniguchi and Sherman 1993). Temperature methods for estimating deep percolation are based on the principal that vertical groundwater flow disturbs the geothermal flux of heat from the earth's core to the land surface.

Geochemical data from the vadose zone can also be interpreted to determine the rate of deep percolation. Water quality of water in the vadose zone can be characterized by extracting soil water from cores or through the use of porous cup lysimeters. Several geochemical tracers are available, including chloride, helium, tritium, and various fertilizers. A particularly common type of geochemical analysis to estimate deep percolation is the chloride mass balance method, whereby the rate of deep percolation can be determined from the chloride content of soil water if the rate of chloride application in dry deposition is known. Most geochemical methods employ the assumption of steady state flow, and any seasonal or long term trends in deep percolation are smoothed out. These methods also rely on the assumption of one-dimensional, vertical flow (lateral flow is neglected).

Several unsaturated zone flow models are available for estimating deep percolation, including UNSAT-H, VS2D, and HYDRUS. These models require a large amount of input, including appropriate boundary conditions, hydraulic conditions, and soil properties to define the model domain; the models provide information on rates and flow paths of deep percolation.

The groundwater table often reflects the occurrence of deep percolation by revealing a mound beneath the infiltration area. For simple situations, when aquifer properties are known, the recharge rate can be calculated based on the slope of the mound using analytical solutions. For more complex cases, such as where there is variable pumping within a heterogeneous aquifer, numerical models are most useful for determining recharge rates.

Case Studies

Evans and Warrick (1980) estimated deep percolation below an irrigated alfalfa field using three vadose zone methods: measurement of Darcy parameters to calculate the Darcian flux, calculating the deep percolation rate based on the measured temperature profiles, and using tritium as a tracer. The authors point out that the hydraulic approach is the most direct but also the most expensive and labor intensive. Each method produces different results; however, the results are within an order of magnitude (Table 1). The average rate of deep percolation is 20 cm/year or 13-20 percent of applied irrigation water (Evans and Warrick 1980).

Table 1. Measured rates of deep percolation (Evans and Warrick 1980).

	Hydraulic Method (cm/yr)	Tritium Method (cm/yr)	Temperature Method (cm/yr)
Deep Percolation	18	38	9

Stonestrom et al. (2003) applied the chloride mass balance method and used nitrate and chloride as tracers to investigate deep percolation in the Amargosa Desert, Nevada. Nine cores were collected beneath irrigated fields, ephemeral channels, and native vegetation. Visual examination of chloride, nitrate, and water content profiles provide qualitative information on the presence of deep percolation at the various locations. For example, in areas of native vegetation, large amounts of chloride had accumulated just below the root zone (the typical "chloride bulge" that is common in arid regions), indicating that deep percolation is not occurring. Areas of deep percolation do not show this chloride bulge since the percolating water flushes the salts to well below the root zone and eventually to the water table. The authors concluded that "deep percolation and recharge is not only occurring beneath areas of irrigation but also beneath ephemeral stream channels" (Stonestrom et al. 2003). Chloride and nitrate concentrations were used as geochemical tracers to estimate rates of deep percolation (D_p, Table 2); 5-12 percent of the amount of water applied to the irrigated fields became return flow to groundwater.

Table 2. Rates of deep percolation and return flow for irrigated fields in the Amargosa Desert (Stonestrom et al. 2003)

	Applied Water (m/yr)	Average chloride concentration (g/m^3)	D_p from Chloride Mass Balance (m/yr)	D_p from chloride or nitrate displacement (m/yr)	% Return on Flow
Field 1 (AFCA 2)	2	116	0.10-0.14	0.19 (Cl)	10-May
Field 2 (AFCA 5)	2	70	0.17-0.23	0.13 (N)	12-Jun

Summary and Conclusions

There are a wide range of methods available to quantify deep percolation and recharge to groundwater. There is often uncertainty associated with the application of any one method so it is helpful to apply multiple techniques. The approach selected will ultimately depend on the available data, time and budget; nevertheless, options are available for most situations.

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