Recharge and groundwater models: an overview

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Abstract Recharge is a fundamental component of groundwater systems, and in groundwater-modeling exercises recharge is either measured and specified or estimated during model calibration. The most appropriate way to represent recharge in a groundwater model depends upon both physical factors and study objectives. Where the water table is close to the land surface, as in humid climates or regions with low topographic relief, a constant-head boundary condition is used. Conversely, where the water table is relatively deep, as in drier climates or regions with high relief, a specified-flux boundary condition is used. In most modeling applications, mixed-type conditions are more effective, or a combination of the different types can be used. The relative distribution of recharge can be estimated from water-level data only, but flux observations must be incorporated in order to estimate rates of recharge. Flux measurements are based on either Darcian velocities (e.g., stream baseflow) or seepage velocities (e.g., groundwater age). In order to estimate the effective porosity independently, both types of flux measurements must be available. Recharge is often estimated more efficiently when automated inverse techniques are used. Other important applications are the delineation of areas contributing recharge to wells and the estimation of paleorecharge rates using carbon-14.

Résumé La recharge est une composante fondamentale des systèmes aquifères, et dans les exercices de modélisation de nappes la recharge est mesurée et déterminée ou estimée lors de la calibration du modèle. La façon la plus appropriée de représenter la recharge dans un modèle de nappe dépend à la fois de facteurs physiques et des objectifs de l'étude. Lorsque la nappe est proche de la surface, comme c'est le cas sous climats humides ou dans les régions à topographie basse, une condition de limite à charge constante est utilisée. Inversement, lorsque la nappe est relativement profonde, comme c'est le cas sous climats plus secs ou dans les régions à fort relief, une condition de limite à flux spécifique est utilisée. Dans la plupart des applications de modélisation, des conditions de type mixte sont plus efficaces, ou bien une combinaison de différents types peut être utilisée. La distribution relative de la recharge peut être estimée uniquement à partir des données de niveau piézométrique, mais des observations sur les flux doivent être introduites pour l'estimation des valeurs de la recharge. Les mesures de flux sont basées soit sur des vitesses de Darcy, par exemple le débit de base d'un cours d'eau, soit sur des vitesses d'écoulement souterrain, par exemple des âges d'eau souterraine. Dans le but d'estimer de manière indépendante la porosité efficace, les deux types de mesures doivent être pris en compte. La recharge est souvent estimée de façon plus efficace lorsque l'on recourt à des techniques d'inversion automatisée. D'autres applications importantes sont la délimitation des zones de recharge de puits et l'estimation des valeurs de paléorecharge par le carbone-14.

Resumen La recarga es una componente fundamental de los sistemas acuífferos. En los trabajos de modelación de aguas subterráneas, la recarga es medida y especificada o estimada durante la fase de calibración. La forma más adecuada de representarla en un modelo depende tanto de los factores físicos como de los objetivos del estudio. Cuando el nivel freático está cercano a la superficie del terreno, como es el caso de climas húmedos o de regiones con un relieve topográfico suave, se aplica una condición de contorno de nivel prescrito. En cambio, se especifica una condición de caudal prescrito cuando la profundidad del nivel freático es grande, como sucede en climas más secos o en regiones con relieves más accidentados. En la mayoría de los casos, la condición de contorno de tipo mixta es la más eficaz, o bien puede utilizarse una combinación de los diversos tipos disponibles. La distribución relativa de la recarga puede ser estimada a partir de datos de nivel, pero se debe incorporar datos de flujo para poder estimar los valores de recarga. Las medidas de flujo se basan bien en velocidades de Darcy (por ejemplo, flujo de base en arroyos), bien en velocidades de filtración (por ejemplo, edad de las aguas

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subterráneas). De cara a la estimación independiente de la porosidad efectiva, se debe disponer de ambos tipos de medidas. A menudo, se estima la recarga de forma más eficaz cuando se aplican técnicas de calibración automática. Otras aplicaciones importantes son la delimitación de las áreas de recarga que son captadas por pozos y la estimación de tasas de paleo-recarga por medio del carbono-14.

Keywords Groundwater recharge · Geologic fabric · Numerical modeling · Inverse modeling

Introduction

For many years, hydrologists have been trying to estimate natural recharge rates to aquifer systems in order to estimate the potential long-term yield of groundwater from those systems (e.g., Theis 1937, 1940). The long-term safe yield of an aquifer system, however, is related not so much to the undisturbed recharge of the natural aquifer system, but rather to the recharge of the disturbed system and the proportion of the discharge that the groundwater extraction centers are able to capture (Bredehoeft et al. 1982; Maddock and Vionnet 1998). In addition, hundreds to thousands of years may be required for a newly disturbed system to come to a new dynamic equilibrium. For these reasons, numerical-modeling efforts were quickly brought to bear upon the problems associated with recharge and the development of groundwater resources (e.g., Taylor and Luckey 1972). The nonlinear interactions among recharge, discharge, boundary conditions, and changes in groundwater storage make solutions to these problems difficult to resolve without the careful accounting of all of the system parameters and their geographical distribution – the very things that can be incorporated into a groundwater model.

Because recharge is an important component of most groundwater models, and because models are frequently used to estimate recharge rates, a careful review and analysis of this topic should assess how recharge is represented in groundwater models and how recharge is estimated using groundwater models. This paper addresses these issues of recharge and groundwater models for regional-scale aquifer systems. Another situation where analysis recharge and groundwater models is important is in semi-arid and arid regions, where the unsaturated zone is commonly relatively thick (e.g., Krishnamurthi et al. 1977; Vauclin et al. 1979; McCord et al. 1997; Tabbagh et al. 1999). In these analyses, the modeling usually focuses on the unsaturated zone and the processes that cause water and solutes to move through the zone (e.g., Russo et al. 2000). These studies are important, for example, in the evaluation of the isolation of nuclear and other toxic wastes. Likewise, the analyses of proposed artificial-recharge schemes have been improved by groundwater modeling exercises (e.g., Latinopoulos 1981; Peters 1998). Although modeling is an important tool for analyses of these local types of studies, these topics are outside the scope of this study, which focuses, rather, on the role of recharge in regional modeling of aquifer systems.

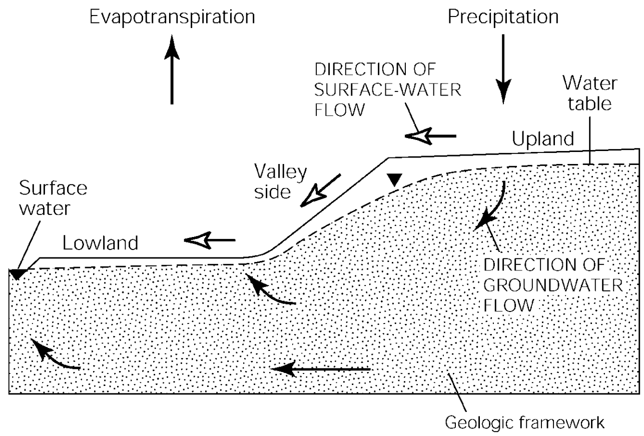

Fig. 1 The dominant factors affecting recharge and groundwater flow. (After Winter 2001)

Representing Recharge in Groundwater Models

In order to represent recharge effectively in a groundwater model, one must consider both the processes that control the rate of recharge and the objectives of the modeling study. The factors that control the rate of recharge are related to the hydrologic landscape of the aquifer system (Winter 2001). The three main factors in the hydrologic landscape that control water flow are classified by Winter (2001) as climate, topography, and the geologic framework. Rainfall supplies the land surface with water, the soil allows the water to infiltrate to the water table, and the deeper geologic framework provides the permeability necessary for deeper flow (Fig. 1). Rainfall and soil infiltration are associated with the land surface. If the climatic and soil conditions allow recharge to reach the water table at a rate that is greater than the saturated zone can transmit the recharge away, then the permeability of the geologic framework controls the recharge rate. This situation results in the condition of a relatively shallow water table, because storage of water underground backs up to the point that excess infiltration is diverted overland. On the other hand, if the saturated zone can transmit more recharge than the climate and soil can provide, then the surface factors (climate and soil) are limiting and control the recharge rate. This condition results in a relatively deep water table. These surface or subsurface types of control on recharge also can, in general, be correlated with a region's rainfall and topographic relief. In regions with relatively arid climates or high topographic relief, the climate controls the rate of recharge, whereas in regions of relatively humid climates or low topographic relief, the geologic framework controls the rate of recharge. In areas of low topography, the water-table gradient also may limit the rate at

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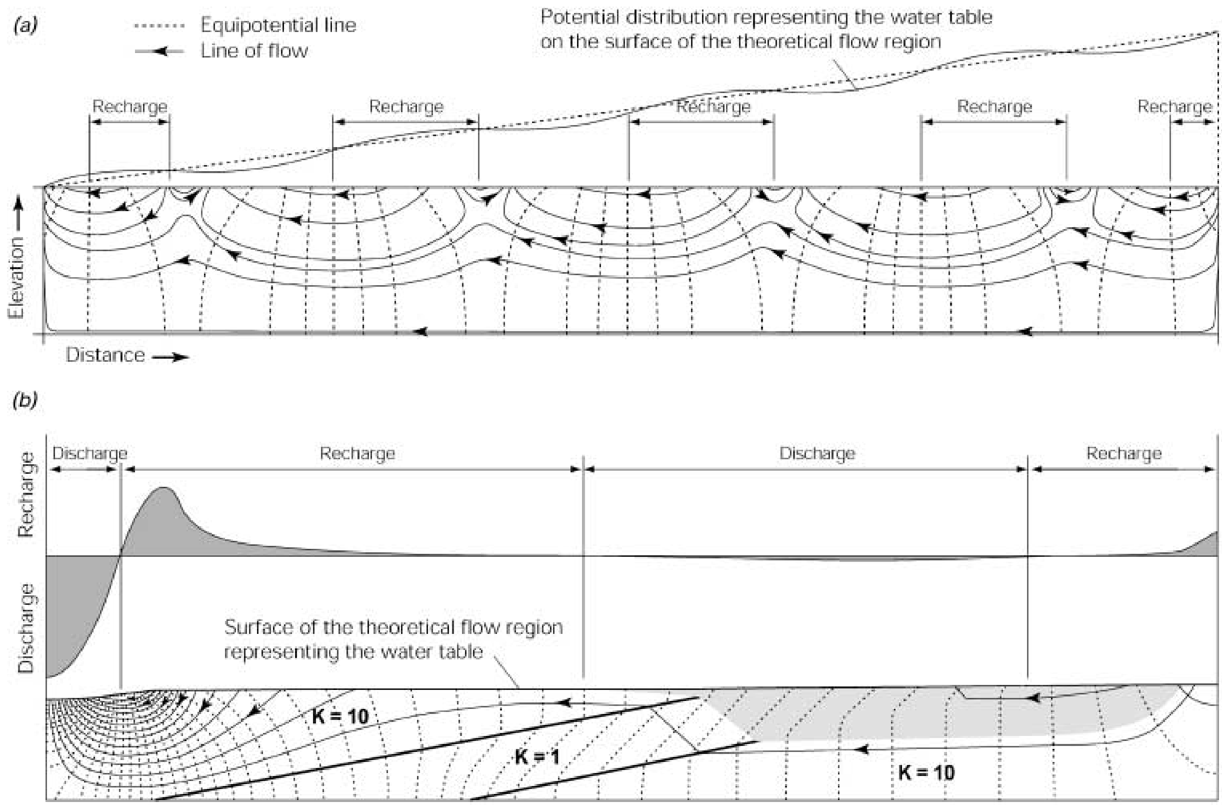

Fig. 2 Early modeling studies of recharge in groundwater flow systems based on **a** an analytical solution to a system with hummocky topography (after Tóth 1963), and **b** a numerical solution to a system with regional heterogeneity (after Freeze and Witherspoon 1968)

which the recharge is transmitted away, if the permeability of the lithology is unusually large. Variability of the topography (Fig. 1) or the geologic framework within the flow system causes different controls to operate in different regions. These various controls on recharge translate directly into the type of mathematical boundary condition that is most appropriate for representing recharge in a groundwater model.

Lithology-Controlled Recharge

Recharge that is controlled by the lithology of the subsurface, and, therefore, associated with conditions of relatively shallow water tables, can be represented by a constant-head boundary condition. The altitude of the water table is known (it usually mimics the land surface closely) with a relative degree of certainty and would not be expected to change appreciably over time. These conditions are difficult to meet in most modeling studies. One situation where this type of boundary condition might be useful is for steady-state models of regional systems where the position of the water table can be estimated fairly well. For example, in early modeling work on understanding the locations and distributions of recharge and discharge areas in regional groundwater flow systems (Tóth 1963; Freeze and Witherspoon 1966, 1967, 1968; Hitchon 1969), the water table was represented with constant-head boundary conditions (Fig. 2). These groundwater models were used to help develop the concepts of local and regional flow systems and how they are related to the distribution of the recharge for those systems. The advantage of this type of boundary condition is that the recharge rate does not have to be estimated from the relatively uncertain hydrologic measurements of evapotranspiration and rainfall/runoff ratios. Rather, the model calculates implicitly the rate of recharge based on the specified values of the other model parameters. The disadvantage of this type of boundary condition is that it assumes the availability of a potentially infinite supply of recharge from the land surface. Thus if the modeler is not careful, erroneously high values of recharge are calculated by the model if the hydraulic parameters are not accurately represented. This type of boundary condition is usually not appropriate for systems where transient drawdowns occur at the water table. In spite of the problems associated with the method, some successful generic modeling studies have used this type of boundary condition. Two classic examples are the interaction of groundwater with lakes (Winter 1978), and the analysis of the effect of groundwater on the genesis of epithermal ore deposits (Garven and Freeze 1984).

Climate-Controlled Recharge

More frequently, recharge is limited to some extent by the amount of infiltration that is available at the land surface. For this situation the boundary condition in a

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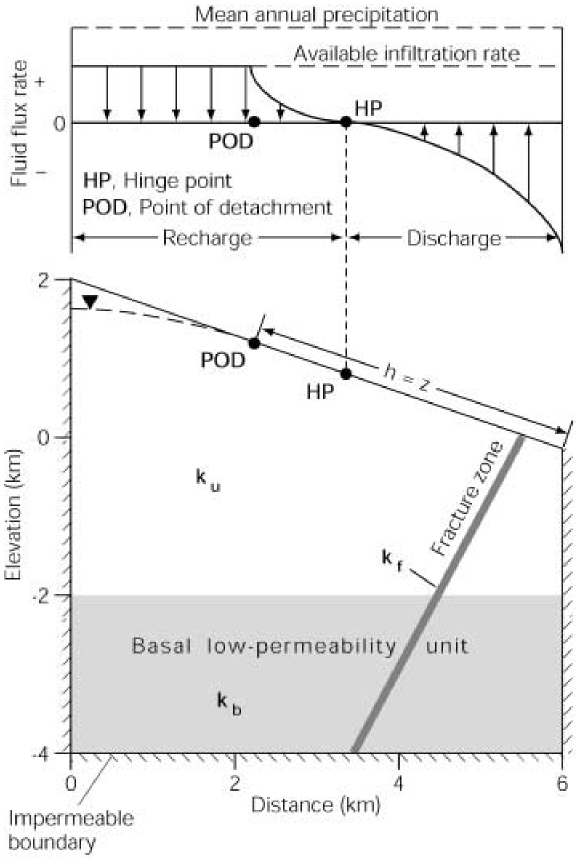

Fig. 3 Representation of recharge in a groundwater model in mountainous terrain where the flux is specified above the point of detachment (*POD*) and a constant-head is specified below the POD. Recharge occurs through the constant-head boundary between the POD and hinge point (*HP*). (After Forster and Smith 1988a)

groundwater model is more effectively represented by specifying the recharge flux. In this case, the areal distribution of recharge is not controlled by the locations of the local and regional flow systems (Fig. 2), but rather by the factors at the land surface that limit delivery of the recharge. The advantage of a specified-flux boundary condition is that, unlike the constant-head boundary condition, the model never implicitly calculates erroneous recharge rates; the best estimates of recharge are specified instead by the modeler. Also, recharge rates are often estimated with more certainty than subsurface permeabilities, thus leading to better-constrained model-simulated fluxes. The difficulty with this method is that an independent effort must be made to obtain an accurate estimate of the recharge rate and distribution. Estimating these rates is often limited by the accuracy of estimated runoff, evapotranspiration, and the infiltration properties of soils.

Modeling studies where transient drawdown cones are developing at pumping centers are an example of where this type of boundary condition is appropriate. In this case, the objective of the study partially determines the most appropriate boundary condition. Steady-state models in mountainous terrains are another area where this type of boundary condition is appropriate (Forster and Smith 1988a, 1988b). In such terrains, where high topographic relief results in high variability of the depth of the water table, an even more accurate approach can be used, in which constant-head conditions are assigned in the valleys and specified flux conditions are assigned in the uplands (Fig. 3). An iterative procedure also can be used to determine the line between the two types of boundary conditions. Abnormally high recharge or discharge rates calculated by the model at the constant-head nodes near the specified flux region indicate that the area of the specified-flux zone should be increased or decreased, respectively. Estimates of recharge in groundwater flow models that include mountainous terrains also may need to take into consideration orographic effects on rainfall (e.g., Manga 1997). Regional precipitation patterns can also be incorporated (e.g., Caro and Eagleson 1981).

Variably Controlled Recharge

Although the two-end member approaches described above fit well into a mathematical framework for representing recharge in groundwater models, both types of control are often present at a single location. Also, a shallow water-table condition may be present in some part of the domain of interest, whereas deep water-table conditions may be present in other parts of the modeled domain. In addition, conditions may alternate temporarily between the two types of control, or the investigator may not be sure which type of control is present. For these situations, the modeler can invoke mixed-boundary conditions or some combination of the mixed and flux boundary conditions.

Many widely used groundwater models, such as MODFLOW (Harbaugh et al. 2000), offer the option of choosing from a variety of mixed-type boundary conditions. These boundary conditions link an external specified head through a hydraulic conductance to the head in the model, which, in turn, affects the flux. These mixed-boundary conditions are more effective at representing many types of natural boundaries. A river, for example, is represented by the head in the river and riverbed conductance. A drain is represented by the land-surface elevation and a drain conductance, where an outward flux is calculated based on the head and the conductance; but any inward flux is set automatically to zero if the head falls below the land surface. Evapotranspiration is represented by two critical head levels, one at the land surface and the other at a so-called extinction depth. The upward flux is specified to a maximum value when the head is at the land surface or above, to a value of zero when the head is below the extinction depth, and to intermediate values when the head is between the two levels. Other conditions that lead to recharge from a surface-water body also have been represented as model options. Examples of these are groundwater–lake interaction (Merritt and Konikow 2000); groundwater–wetland in-

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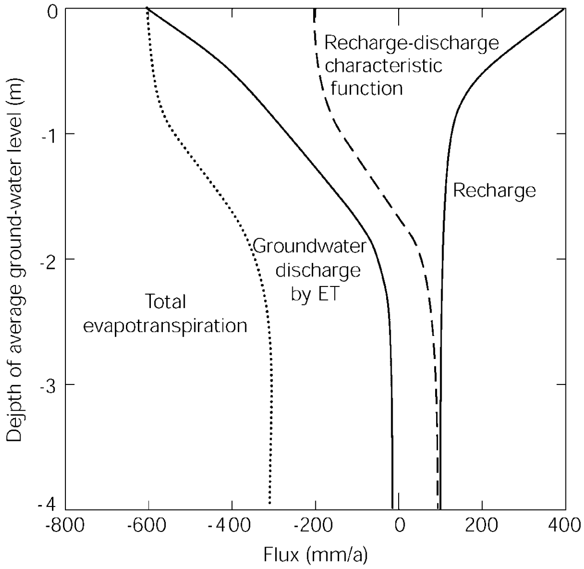

Fig. 4 Example of the relation between recharge, evapotranspiration (*ET*), and discharge as a function of the depth of the water table below land surface. Total evapotranspiration includes infiltration that returns to the atmosphere without reaching the water table. The *dashed line* is a composite function obtained by superimposing the recharge and groundwater discharge by evapotranspiration curves. The positions of these curves would shift as a function of local vegetation and climate. (After Simonffy and Martin 1995)

teraction (Restrepo et al. 1998); and groundwater–stream interaction (Prudic 1989), where the total flow in the stream also is accounted for.

Although some of these mixed-boundary conditions do not represent recharge directly, they are used in conjunction with specified-flux recharge conditions to more realistically represent the aquifer system. More than one type of boundary condition can be included at the same location in a model (Jorgensen et al. 1989). When the water table is close to the land surface, for example, evapotranspiration and recharge occur simultaneously (Kovacs 1986). The net flux from the combination of these two controls is a function of the depth to the water table (Fig. 4). The effects of both recharge and evapotranspiration are handled in this way when both boundary condition types are specified over broad model regions. The result is that the model implicitly calculates the rates and distributions of both recharge and evapotranspiration, because they are linked to the land-surface elevation. A drain condition could also be specified simultaneously, if desired, that would allow for discharge to be a function of the calculated level of the water table above the land surface.

An example of the approach described above was used in a groundwater model of a region in south-central Hungary (Sanford et al. 2001b). The topography of the region (Fig. 5a) was used in specifying the evapotranspiration boundary condition. A single value of recharge also was assigned to the entire active model area. The model then calculated the net recharge and discharge over the area (Fig. 5b) and the resulting water-table configuration (Fig. 5d). In this case, 300 water levels were used to calibrate the model, and a close match with the observed water table resulted (Fig. 5c). Furthermore, the water-table configuration follows the land surface closely, and the net discharges occur in the valleys, as expected. In addition, the water table beneath the hilltops is deeper, and, accordingly, the evapotranspiration is zero and the net recharge is equal to the ubiquitous specified value of recharge.

Estimating Recharge with Models

Recharge measurements in the field still contain an appreciable amount of uncertainty, and much study on the subject is ongoing, as evidenced by this theme issue. Along with the variety of approaches used to make measurements in the field, investigators have used groundwater models to help estimate recharge. If the other model parameters are known well enough, then the model could be used to constrain the recharge. This approach applies to constraining not only the rate of the recharge, but also the distribution of recharge and the fate of recharge when multiple points of discharge are present in the aquifer system.

Estimating the Distribution of Recharge

The earliest regional groundwater modeling studies (Fig. 2) indicated that models could be used to help estimate the distribution of recharge. This model use applies primarily to cases where the permeability distribution and the position of the water table are well known. In order to use a model to estimate a reliable rate of recharge, the hydraulic conductivities of the aquifer system must be well known. The recharge rate is indeterminate if only water-level information is available (Darcy's law states that head gradients are a function of both fluid flux and hydraulic conductivity). The best way to constrain the rate of recharge is to obtain flux measurements of some type (e.g., stream baseflows or groundwater ages). However, the distribution of the recharge can be estimated without flux data if the distribution and degree of the aquifer heterogeneity are known. In this situation, specification of the water-level conditions yields an estimate of the distribution of recharge (Allison 1987). The study in Hungary discussed earlier (Fig. 5) is an example of specifying water-level conditions. The initial calibrations for that study were done with only water-level data and the assumption of a homogeneous but vertically anisotropic permeability field. Initially, the estimates of the rates of the recharge were indeterminate, but because the water levels were well constrained (and linked closely to the land surface), a good estimate of the net recharge/discharge distribution for the system was obtained (Fig. 5b). The magnitude of recharge was constrained later using groundwater ages.

One approach for the estimation of recharge in this manner has been formalized to work with established

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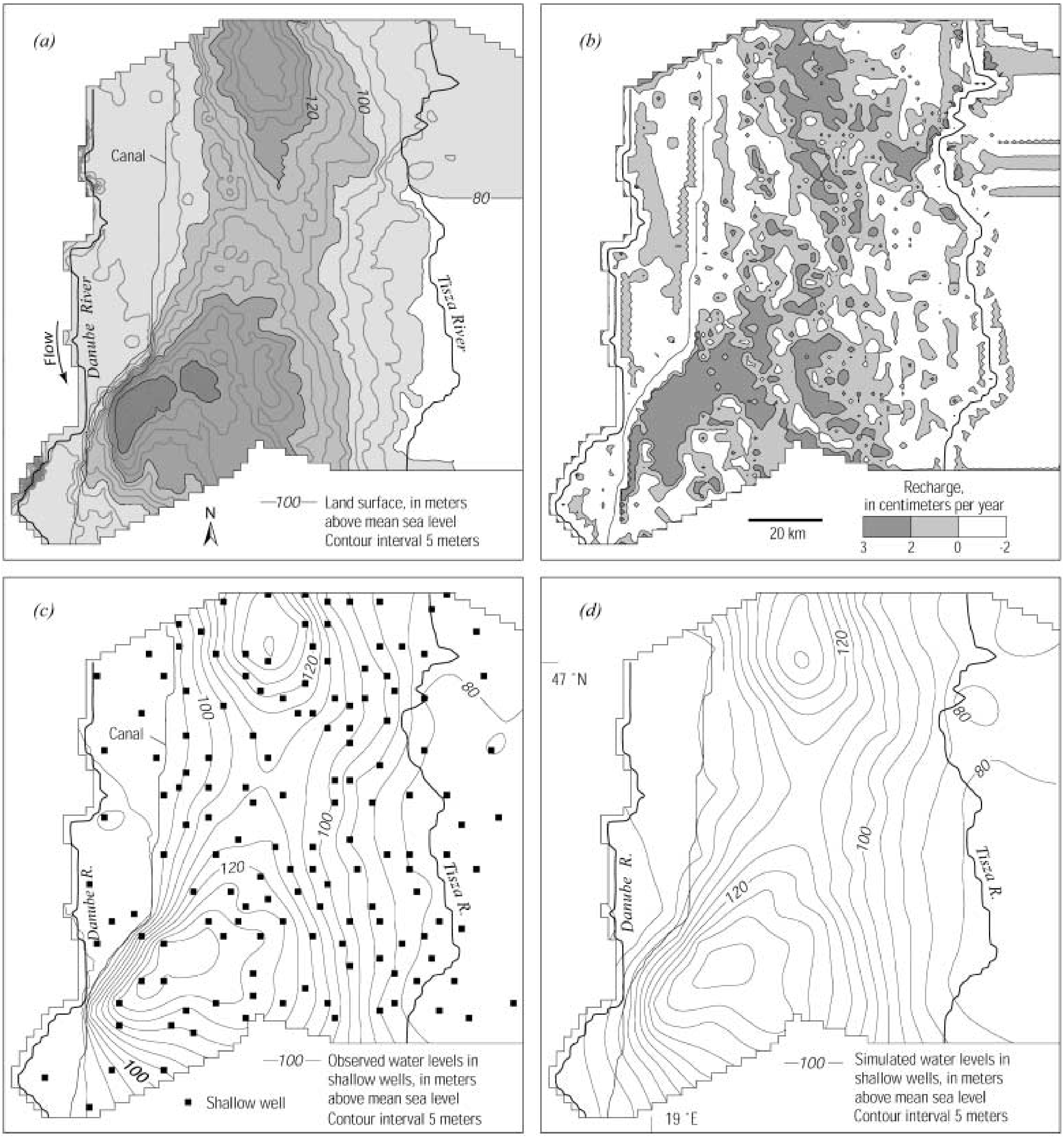

Fig. 5 Numerical modeling results from the Danube-Tisza interfluvial region of south-central Hungary (Sanford et al. 2001b), showing **a** topographic relief, **b** model-calculated recharge and discharge, **c** observed water-table configuration, and **d** simulated water-table configuration

groundwater models (Stoertz and Bradbury 1989). The approach can be thought of as a mass-balance calculation at each model cell (Fig. 6). Fluxes between each model cell (e.g., Q_{BC} and Q_{CD}) are calculated based on the transmissivity and water-table values specified by the user. The difference between these fluxes must then be the amount of recharge or discharge entering the cell. This approach assumes a two-dimensional areal flow system and that a value for the water-table is specified for each cell. The limitations of this approach are that small errors in water-table gradients or the transmissivity distribution lead to appreciable errors in the recharge estimates (Weir 1989). In most cases, the uncertainties associated with knowing the transmissivity distribution overwhelm the certainties in the recharge rates calculated using this method.

Estimating the Rate of Recharge

Darcy's law states that fluid flux, such as recharge, in an aquifer system can be calculated if both the head gradients and hydraulic conductivities are known. However,

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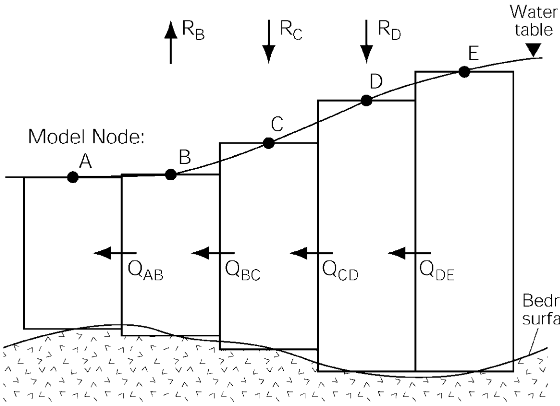

Fig. 6 An approach for calculating recharge from a groundwater model based on specified values for the water-table depth and transmissivities – for example, recharge at C (R_C) is the difference between the fluxes at Q_{CD} and Q_{BC} obtained by using Darcy's law at those points. (After Stoertz and Bradbury 1989)

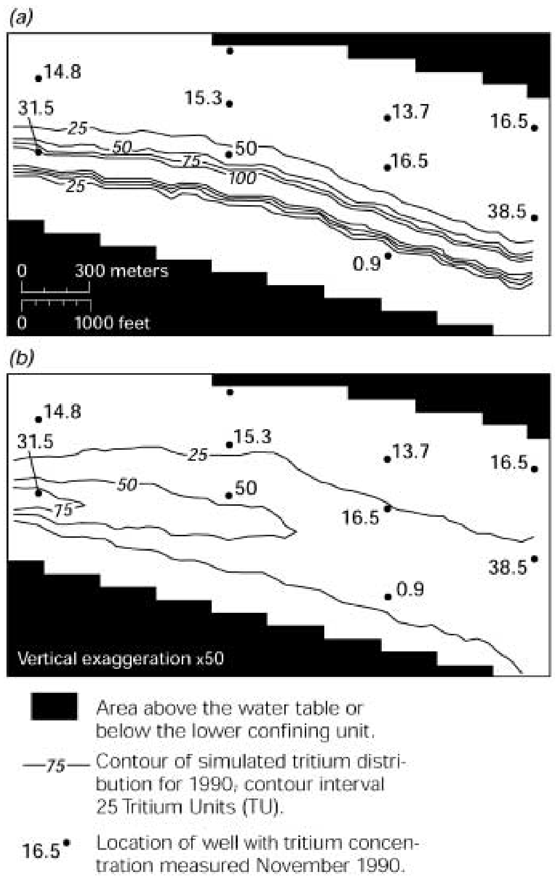

Fig. 7 Results from a two-dimensional groundwater model on the Delmarva peninsula, USA, where tritium is used as an age tracer to calibrate a model **a** with and **b** without hydrodynamic dispersion. (After Reilly et al. 1994)

the uncertainties that are usually associated with accurate and scale-appropriate hydraulic-conductivity values leave the hydrologist looking for other approaches to constrain more accurately the recharge rates. Measuring the concentrations of environmental tracers that indicate groundwater age has been one increasingly popular approach. The most popular of these tracers include tritium (Schmalz and Polzer 1969), tritium/helium (Solomon et al. 1993), chlorofluorocarbons (Plummer and Busenberg 1999), and carbon-14 (Kalin 1999). The ages determined by the applications of techniques represent integrated times of travel of the water and solutes within the aquifer system from the recharge area to the precise point in the aquifer system where the sample was collected. These ages are used to back-calculate regional recharge rates using a groundwater-modeling calibration procedure if an independent estimate of effective porosity is available. Groundwater models are used routinely to calculate seepage velocities as well as head distributions. These velocities are used to simulate travel paths and associated times that are then compared directly with the groundwater ages (e.g., Reilly et al. 1994). Models that either neglect or include hydrodynamic dispersion are used effectively in these calibration procedures (Fig. 7). For short flow paths and tracers with transient input signals, dispersion is important to solute transport within the aquifer system. However, for tracers with longer flow paths and relatively continuous input signals (i.e., carbon-14), dispersion usually has a much smaller effect than radioactive decay has on changes in concentration. During such calibration procedures, the model parameters (recharge and hydraulic conductivities) are adjusted until an acceptable match with both travel times and water levels is produced (e.g., Parkhurst et al. 1996; Sheets et al. 1998).

Determining the Fate of Recharge

Within the last 50 years, pollution of groundwater systems has become as important an issue as sustainable water supply. This development has led to the use of groundwater models to investigate the fate of groundwater recharge, with the focal point being the discharge at a well or spring. The problem usually addressed is the delineation of the area that contributes recharge to a well or well field (Lerner 1992; Reilly and Pollock 1993; Barlow 1995; Franke et al. 1998). The identified area is then targeted for protection from future potential pollution, or potential polluters are identified for areas (such as wells) already contaminated. The location and distribution of such a source area is very sensitive to changes in the model parameters, especially to aquifer heterogeneity, recharge, and the locations and nature of surface-water bodies and their interactions with the groundwater. Before groundwater models were used for this type of analysis, oversimplified methods were used, such as drawing circles around wells with radii that were based on a single long-term estimated recharge rate. Groundwater modeling efforts, and especially three-dimensional investigations, have demonstrated how even relatively simple subsurface hydrogeology can result in complex shapes for the model-simulated source areas. Results from a study at Cape Cod, Massachusetts, USA, illustrate the types of elongated and distorted shapes these

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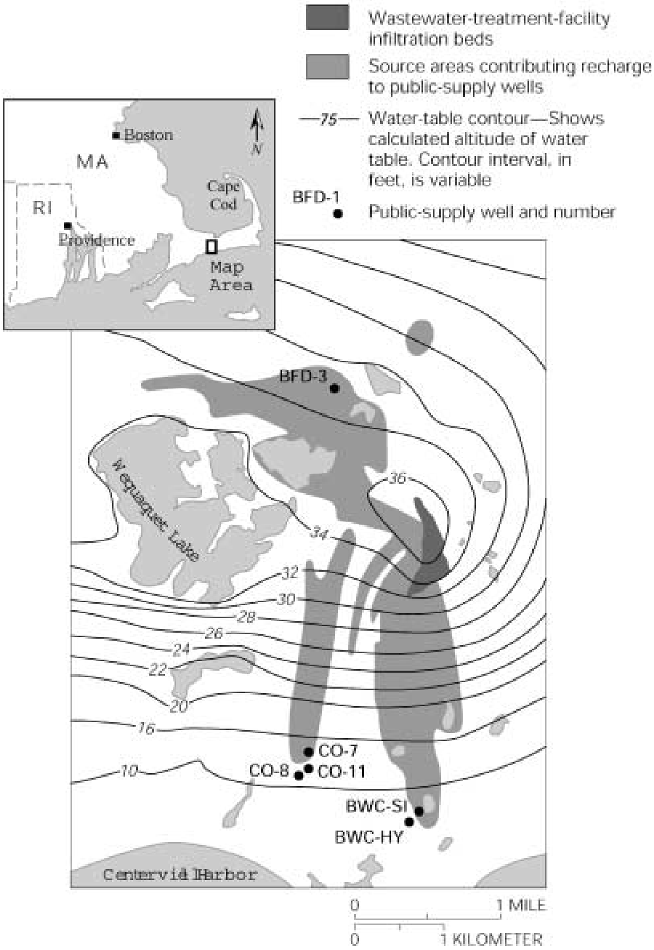

Fig. 8 Results from a three-dimensional modeling study in Cape Cod, Massachusetts, USA, where the delineated areas contributing recharge to public-supply wells assume complicated shapes. (After Barlow 1995)

projected areas can assume (Fig. 8). Some of the well locations do not fall within the projected recharge area for that well. Further studies indicate that typical annual transient fluctuations in recharge usually have only a small effect on the locations of these projected areas (Reilly and Pollock 1995), although such transients can have an effect on the dispersion of contaminants and, therefore, their concentration levels when they reach the wells (Goode and Konikow 1990; Kim et al. 2000). Advective path-line codes linked to groundwater models (e.g., Pollock 1994) have made these types of analyses a fairly straightforward exercise.

Inverse Methods for Estimating Recharge

The ability to use groundwater models to estimate recharge has been made easier by the development of inverse modeling techniques, where nonlinear regression algorithms are used to automatically obtain a best fit between observed data and simulated observations (Cooley 1977; Yeh 1986). This type of approach not only has the advantage of producing a mathematical best fit between the observations and the model, but also produces information on the sensitivities of the observations to the model parameters. The sensitivities yield information on the relative certainty with which the parameters are estimated given the specific observations (e.g., water levels) that are present and the uncertainties in their measurements. This type of modeling approach has been incorporated into groundwater models (e.g., Hill 1992; Hill et al. 2000), and guidelines are present for calibrating models using such approaches and tools (Hill 1998). During inverse modeling exercises, recharge and hydraulic conductivity values are usually estimated simultaneously, because the investigator is usually trying to constrain the values of both of these parameters. One problem that arises is that only the ratio of recharge to hydraulic conductivity can be estimated if only water levels are available as observations. Flux observations must be available in order to obtain a unique estimate of recharge, and, even then, when the total number of observations is dominated by water levels, the uncertainty in the recharge estimate is usually high. One common type of flux observation used in inverse modeling is the baseflow to streams (e.g., Jackson and Rushton 1987; Arnold et al. 2000). The uncertainty typically associated with baseflow observations, however, carries through to the uncertainty in the recharge estimate.

As discussed earlier, another important source of flux information is groundwater ages obtained from environmental-tracer concentrations in samples from wells. When these fluxes are included in inverse modeling exercises, the correlation between the parameters being estimated and the uncertainty in those parameter values is usually reduced dramatically. Computer programs for inverse modeling are now available that incorporate these types of observations. The most common are general programs that are linked to any mathematical model that has adjustable parameters and produces simulated observations that are compared with field observations (Doherty 1994; Poeter and Hill 1998). Other models are available that use advective travel paths as observations (Anderman and Hill 1997). Investigations of inverse modeling using chemical tracers reveal that such observations are important for estimating system fluxes, but other parameters, like porosity, associated with the calculation of the seepage velocity, are still indeterminate with only chemical tracer and water-level observations (Medina and Carrera 1996; Portniaguine and Solomon 1998). The ideal situation for estimating the most number of parameters is to be able to use both baseflow measurements and groundwater travel times, because this allows for an independent estimate of porosity. One alternative to the use of baseflow observations is the use of temperature observations (Woodbury and Smith 1988), which are another indicator of the Darcian flux. This approach works as long as the thermal regime is not conduction dominated. In granular porous media, the effective porosity is often measured directly from cores or estimated by grain-size analysis with some certainty, and

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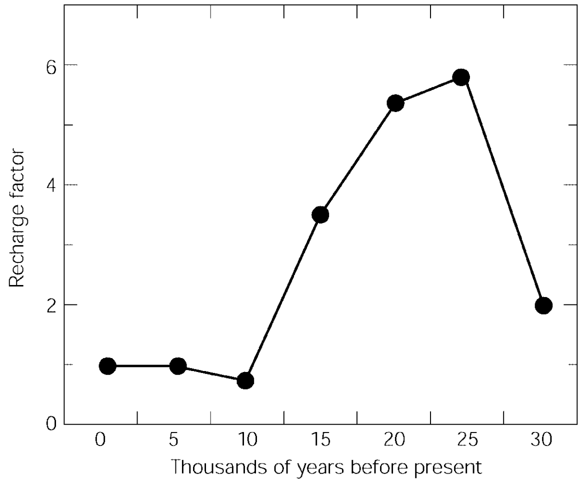

Fig. 9 Results from a three-dimensional groundwater model of the Middle Rio Grande Basin, New Mexico, USA, where carbon-14 ages are used to calibrate paleorecharge over the last 30,000 years. The recharge factor is the proportion of recharge required for a best fit to the data compared to present-day recharge. (After Sanford et al. 2001a)

then the need for baseflow or temperature observations in addition to travel times may not be as critical to the investigation. In fractured rocks, however, the effective porosity is much more difficult to characterize in the field, and then having both seepage flux and Darcian flux observations would be important for an effective estimation of the transport parameters.

Paleorecharge

For water-supply development problems where a current hydrologic budget of the system is being assessed, a steady-state recharge rate is usually assumed. On the other hand, evidence is present from carbon-14 and other environmental isotopes in aquifers studied throughout the world (de Vries 1984; Heinl and Brinkmann 1989) that recharge at some locations has varied appreciably over tens of thousands of years, most notably during the typically wetter climate of the most recent ice age. Such variations in climate and recharge are of interest for long-term recharge assessments for contaminant-transport problems, such as the isolation of nuclear wastes in arid regions (e.g., Czarnecki 1984). Groundwater models are now starting to be applied in conjunction with environmental tracers, especially carbon-14, to try to assess the likelihood that the recharge in a regional aquifer system has changed over the past approximately 30,000 years (van der Kemp et al. 2000; Zhu 2000). This approach is more viable in systems where the recharge is climate-controlled, typically in relatively arid regions with high topographic relief.

In some cases, if enough carbon-14 data are available, the change in recharge rates can be quantified over the past few tens of thousands of years. In a recent study of the Middle Rio-Grande Basin of New Mexico, USA (Sanford et al. 2001a), about 200 carbon-14 concentrations from well samples were used along with 200 water-level observations to calibrate a predevelopment groundwater model of the Albuquerque Basin. In this area, recharge is predominantly along the mountain fronts flanking the basin, and the recharge is specified at those model locations. An inverse modeling exercise was undertaken using UCODE (Poeter and Hill 1998) to estimate those recharge values. To estimate the variations in recharge over time, a multiplier was assigned to all of the recharge for each 5,000-year interval of a long-term transient simulation (Fig. 9). Estimates of the multipliers were calibrated to the carbon-14 and water-level data. The optimal results suggest that the recharge was approximately five times higher during the last glacial maximum about 20,000 years ago, and then it tapered off to near present-day values by about 10,000 years ago.

Summary

The manner in which recharge is incorporated into groundwater models depends upon the type of process that is controlling the recharge and on the objectives of the modeling study. In regions that tend to be arid or have high topographic relief, the water table is usually relatively deep, and the rate of recharge is controlled by the amount of water that the climate provides and that the soil then delivers to the water table. This type of recharge is often simulated using a specified-flux boundary condition. At the other extreme, in regions that have a relatively wet climate or have lower relief, the water table is usually shallow, and the rate of recharge is controlled by the amount of water that the aquifer system can transmit to the discharge area. This transmission is controlled by the permeability of the geologic framework. This type of recharge is sometimes simulated using a constant-head boundary condition. In most situations, however, a combination of these boundary conditions is required for accurate model simulation. In those cases, mixed-type boundary conditions are included that account for surface-water/groundwater interaction or evapotranspiration.

Groundwater models are used routinely to try to estimate regional recharge rates. The distribution of recharge can be estimated using water-level information (for example, a water-table map), but the accuracy of the results depends greatly on the accuracy of the information and the magnitude and distribution of the aquifer permeability. The areas that contribute recharge to wells can also be delineated using groundwater models that are used in conjunction with path-line tracking software. The rates of recharge are estimated only when some type of flux measurements are available. One type of measurement often used is groundwater baseflow to streams. Another type of flux measurement receiving increased use is the travel time of water to wells based on age determination. Using groundwater ages increases greatly the cer-

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tainty associated with estimates of recharge rates. Any of these measurements can be included in automated inverse-modeling exercises. The baseflows are used to estimate the Darcian flux, whereas the travel times are used to estimate the seepage flux. In order to estimate effective porosity independently, both types of flux data must be included. In certain cases, paleorecharge rates can also be estimated using carbon-14-based ages with inverse modeling.

References

Allison H (1987) The principles of inverse modelling for estimation of recharge from hydraulic head. In: Simmers I (ed) Estimation of natural groundwater recharge. NATO ASI Series C 222:271–282

Anderman ER, Hill MC (1997) ADVective-transport observation (ADV) package, a computer program for adding advective-transport observations of steady-state flow fields to the three-dimensional ground-water flow parameter estimation model MODFLOWP. US Geol Surv Open-File Rep 97–14

Arnold JG, Muttiah RS, Srinivasan R, Allen PM (2000) Regional estimation of base flow and groundwater recharge in the Upper Mississippi River basin. J Hydrol 227:21–40

Barlow PM (1995) Particle-tracking analysis of contributing areas of public-supply wells in simple and complex flow systems, Cape Cod, Massachusetts. US Geol Surv Water-Supply Pap 2434

Bredehoeft JD, Papadopulos SS, Cooper HH Jr (1982) Groundwater: the water-budget myth. US National Research Council studies in geophysics: scientific basis of water-resource management. National Academy Press, Washington, DC, pp 51–57

Caro R, Eagleson PS (1981) Estimating aquifer recharge due to rainfall. J Hydrol 53:185–211

Cooley RL (1977) A method of estimating parameters and assessing reliability for models of steady state groundwater flow; 1. Theory and numerical properties. Water Resour Res 13: 318–324

Czarnecki JB (1984) Simulated effects of increased recharge on the ground-water flow system of Yucca Mountain and vicinity, Nevada-California. US Geol Surv Water-Resour Invest Rep 84–4344

De Vries JJ (1984) Holocene depletion and active recharge on the Kalahari groundwaters; a review and an indicative model. J Hydrol 70:221–232

Doherty J (1994) PEST. Watermark Computing, Corinda, Australia

Forster C, Smith L (1988a) Groundwater flow systems in mountainous terrain; 1. Numerical modeling technique. Water Resour Res 24:999–1010

Forster C, Smith L (1988b) Groundwater flow systems in mountainous terrain; 2. Controlling factors. Water Resour Res 24:1011–1023

Franke OL, Reilly TE, Pollock DW, LaBaugh JW (1998) Estimating areas contributing recharge to wells – lessons from previous studies. US Geol Circ 1174

Freeze RA, Witherspoon PA (1966) Theoretical analysis of regional groundwater flow; 1. Analytical and numerical solutions to the mathematical model. Water Resour Res 2:641–656

Freeze RA, Witherspoon PA (1967) Theoretical analysis of regional groundwater flow; 2. Effect of water-table configuration and subsurface permeability variation. Water Resour Res 3:623–634

Freeze RA, Witherspoon PA (1968) Theoretical analysis of regional ground water flow; 3. Quantitative interpretations. Water Resour Res 4:581–590

Garven G, Freeze RA (1984) Theoretical analysis of the role of groundwater flow in the genesis of stratabound ore deposits; 1. Mathematical and numerical model. Am J Sci 284:1085–1124

Goode DJ, Konikow LF (1990) Apparent dispersion in transient ground-water flow. Water Resour Res 26:2339–2351

Harbaugh AW, Banta ER, Hill MC, McDonald MG (2000) MODFLOW 2000. The US Geological Survey modular ground-water model – user guide to modularization concepts and the ground-water flow process. US Geol Surv Open-File Rep 00–92

Heinl M, Brinkmann PJ (1989) A groundwater model of the Nubian aquifer system. Hydrol Sci J 34:425–447

Hill MC (1992) A computer program (MODFLOWP) for estimating parameters of a transient, three-dimensional, ground-water flow model using nonlinear regression. US Geol Surv Open-File Rep 91–484

Hill MC (1998) Methods and guidelines for effective model calibration. US Geol Surv Open-File Rep 98–4005

Hill MC, Banta ER, Harbaugh AW, Anderman ER (2000) MODFLOW-2000. The US Geological Survey modular groundwater model – user guide to the observation, sensitivity, and parameter-estimation processes and three post-processing programs. US Geol Surv Open-File Rep 00–184

Hitchon B (1969) Fluid flow in the western Canada sedimentary basin; 1. Effect of topography. Water Resour Res 5:186–195

Jackson D, Rushton KR (1987) Assessment of recharge components for a chalk aquifer unit. J Hydrol 92:1–15

Jorgensen DG, Signor DC, Imes JL (1989) Accounting for intracell flow in models with emphasis on water table recharge and stream–aquifer interaction; 1. Problems and concepts. Water Resour Res 25:669–676

Kalin RM (1999) Radiocarbon dating of groundwater systems. In: Cook P, Herczeg AL (eds) Environmental tracers in subsurface hydrology. Kluwer, Dordrecht, pp 111–144

Kim K, Anderson MP, Bowser CJ (2000) Enhanced dispersion in groundwater caused by temporal changes in recharge rate and lake levels. Adv Water Resour 23:625–635

Kovacs G (1986) Methods to characterize groundwater–atmosphere interactions. In: Gorelick SM (ed) Conjunctive water use; understanding and managing surface water–groundwater interactions, Proc 2nd Scientific Assembly of the International Association of Hydrological Sciences, Budapest, Hungary, July 1986, IAH Publ 156, pp 259–276

Krishnamurthi N, Sunada DK, Longenbaugh RA (1977) Mathematical modeling of natural groundwater recharge. Water Resour Res 13:720–724

Latinopoulos P (1981) The response of groundwater to artificial recharge schemes. Water Resour Res 17:1712–1714

Lerner DN (1992) Well catchments and time-of-travel zones in aquifers with recharge. Water Resour Res 28:2621–2628

Maddock T III, Vionnet LB (1998) Groundwater capture processes under a seasonal variation in natural recharge and discharge. Hydrogeol J 6:24–32

Manga M (1997) A model for discharge in spring-dominated streams and implications for the transmissivity and recharge of Quaternary volcanics in the Oregon Cascades. Water Resour Res 33:1813–1822

McCord JT, Gotway CA, Conrad SH (1997) Impact of geologic heterogeneity on recharge estimation using environmental tracers; numerical modeling investigation. Water Resour Res 33:1229–1240

Medina A, Carrera J (1996) Coupled estimation of flow and solute transport parameters. Water Resour Res 32:3063–3076

Merritt ML, Konikow LF (2000) Documentation of a computer program to simulate lake–aquifer interaction using the MODFLOW ground-water flow model and the MOC3D solute-transport model. US Geol Surv Water-Resour Invest Rep 00–4167

Parkhurst DL, Christenson SC, Breit GN (1996) Ground-water-quality assessment of the Oklahoma aquifer, Oklahoma: geochemical and hydrologic investigations. US Geol Surv Water-Supply Pap 2357

Peters JH (ed) (1998) Artificial recharge of groundwater. In: Proc Int Symp on Artificial Recharge, Amsterdam, The Netherlands, 21–25 Sept, AA Balkema, Rotterdam

DOI 10.1007/s10040-001-0173-5

Plummer LN, Busenberg E (1999) Chlorofluorocarbons. In: Cook P, Herczeg AL (eds) Environmental tracers in subsurface hydrology. Kluwer, Dordrecht, pp 441–478

Poeter EP, Hill MC (1998) Documentation of UCODE, a computer code for universal inverse modeling. US Geol Surv Water-Resour Invest Rep 98–4080

Pollock DW (1994) User's guide for MODPATH/MODPATH-PLOT, version 3: a particle tracking post-processing package for MODFLOW, the US Geological Survey finite-difference ground-water flow model. US Geol Surv Open-File Rep 94–464

Portniaguine O, Solomon DK (1998) Parameter estimation using groundwater age and head data, Cape Cod, Massachusetts. Water Resour Res 34:637–645

Prudic DE (1989) Documentation of a computer program to simulate stream–aquifer relations using the modular finite-difference ground-water flow model. US Geol Surv Open-File Rep 88–729

Reilly TE, Pollock DW (1993) Factors affecting areas contributing recharge to wells in shallow aquifers. US Geol Surv Water-Supply Pap 2412

Reilly TE, Pollock DW (1995) Effect of seasonal and long-term changes in stress on sources of water to wells. US Geol Surv Water-Supply Pap 2445

Reilly TE, Plummer LN, Phillips PJ, Busenberg E (1994) The use of simulation and multiple environmental tracers to quantify groundwater flow in a shallow aquifer. Water Resour Res 30:421–433

Restrepo JI, Montoya AM, Obeysekera J (1998) A wetland simulation package for the MODFLOW ground water model. Ground Water 36:764–770

Russo D, Zaidel J, Laufer A (2000) Numerical analysis of flow and transport in a combined heterogeneous vadose zone–groundwater system. Adv Water Resour 24:49–62

Sanford WE, Plummer NL, McAda DP, Bexfield LM, Anderholm SK (2001a) Estimation of hydrologic parameters for the ground-water model of the Middle Rio Grande Basin using carbon-14 and water-level data. In: Cole JC (ed) US Geological Survey Middle Rio Grande Basin Study, Proc 4th Annu Worksh, Albuquerque, New Mexico, US Geol Surv Open-File Rep 00–488, pp 4–6

Sanford WE, Revesz K, Deak J (2001b) Inverse modelling using ^{14}C ages: application to groundwater in the Danube-Tisza interfluvial region of Hungary. In: Seiler KP, Wohnlich S (eds) New approaches characterizing groundwater flow, Proc 31st Annu Congr of the International Association of Hydrogeologists, Munich, 10–14 Sept, pp 401–404

Schmalz BL, Polzer WL (1969) Tritiated water distribution in unsaturated soil. Soil Sci 108:43–47

Sheets RA, Bair ES, Rowe GL (1998) Use of $^{3}H/^{3}He$ ages to evaluate and improve groundwater flow models in a complex buried-valley aquifer. Water Resour Res 34:1077–1089

Simonffy Z, Martin T (1995) Environmental limits of groundwater withdrawals. In: Lal R, Nemeth T (eds) Proc Worksh on Conservation Tillage for Sustaining Soil and Water Quality, Ministry for Environmental Protection, Budapest, pp 239–248

Solomon DK, Schiff SL, Poreda RJ, Clarke WB (1993) A validation of the $^{3}H/^{3}He$ method of determining groundwater recharge. Water Resour Res 29:2851–2962

Stoertz MW, Bradbury KR (1989) Mapping recharge areas using a ground-water flow model – a case study. Groundwater 27:220–228

Tabbagh A, Bendjoudi H, Benderitter Y (1999) Determination of recharge in unsaturated soils using temperature monitoring. Water Resour Res 35:2439–2446

Taylor OJ, Luckey RR (1972) A new technique for estimating recharge using a digital model. Ground Water 10:22–26

Theis (1937) Amount of ground-water recharge in the southern High Plains. Trans Am Geophys Union 18:564–568

Theis (1940) The source of water derived from wells: essential factors controlling the response of an aquifer to development. Civil Eng 10:277–280

Tóth J (1963) A theoretical analysis of groundwater flow in small drainage basins. J Geophys Res 68:4795–4812

van der Kemp WJM, Appelo CAJ, Walraevens K (2000) Inverse chemical modeling and radiocarbon dating of palaeogroundwaters: the Tertiary Ledo-Paniselian aquifer in Flanders, Belgium. Water Resour Res 36:1277–1287

Vauclin M, Khanji D, Vachaud G (1979) Experimental and numerical study of a transient, two-dimensional unsaturated–saturated water table recharge problem. Water Resour Res 15:1089–1101

Weir GJ (1989) The direct inverse problem in aquifers. Water Resour Res 25:749–753

Winter TC (1978) Numerical simulation of steady state three-dimensional groundwater flow near lakes. Water Resour Res 14:245–254

Winter TC (2001) The concept of hydrologic landscapes. J Am Water Resour Assoc 37:335–349

Woodbury AD, Smith L (1988) Simultaneous inversion of hydrogeologic and thermal data: 2. Incorporation of thermal data. Water Resour Res 24:356–372

Yeh WWG (1986) Review of parameter identification procedures in groundwater hydrology; the inverse problem. Water Resour Res 22:95–108

Zhu C (2000) Estimate of recharge from radiocarbon dating of groundwater and numerical flow and transport modeling. Water Resour Res 36:2607–2620

 DOI 10.1007/s10040-001-0173-5