Groundwater recharge: an overview of processes and challenges

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Abstract Since the mid-1980s, a relative explosion of groundwater-recharge studies has been reported in the literature. It is therefore relevant to assess what is now known and to offer further guidance to practitioners involved in water-resource development. The paper summarizes current understanding of recharge processes, identifies recurring recharge-evaluation problems, and reports on some recent advances in estimation techniques. Emphasis is accorded to (semi-)arid regions because the need for information is greatest in those areas – groundwater is often the only water source, is vulnerable to contamination, and is prone to depletion. Few studies deal explicitly with groundwater recharge in temperate and humid zones, because recharge is normally included in regional groundwater investigations as one component of the water balance. The resolution of regional water-balance studies in (semi-)arid areas is, in contrast, often too low to quantify the limited recharge component with sufficient precision.

Despite the numerous studies, determination of recharge fluxes in (semi-)arid regions remains fraught with uncertainty. Multiple tracer approaches probably offer the best potential for reliable results in local studies that require 'at-point' information. However, many investigations indicate that these approaches are not straightforward, because in some cases preferential flow contributes as much as 90% of the estimated total recharge. Tracer results (e.g. Cl^-, ^3H) must therefore be interpreted with care in areas with multi-modal flow in the vadose zone. Moreover, accurate estimation of total chloride deposition is essential, and tritium may be influenced by vapour transport at low flux rates. In addition, paleoclimatic and paleohydrological conditions may cause discrepancies between measured actual processes and calculated long-term averages.

The frequently studied issues of *localized* recharge and spatial variability need not be a problem if concern is with regional estimates. The key for practitioners is the project objective, which dictates whether 'at-point' or area-/groundwater-based estimation methods are appropriate. Many *indirect* (wadi) recharge studies reported in the literature are site specific; the relationship between 'at point' hydraulic properties and channel-reach losses demands further investigation.

Résumé Depuis les années 1980, une explosion relative des études de recharge de nappes a été notée dans la littérature. Il est par conséquent pertinent d'évaluer ce qui est connu et de donner davantage de conseils aux praticiens impliqués dans le développement des ressources en eau. Ce papier résume les connaissances courantes sur les processus de recharge, identifie les problèmes classiques d'évaluation de la recharge et donne des informations sur quelques avancées récentes concernant les techniques d'estimation. L'accent est mis sur les régions arides et semi-arides parce que le besoin d'informations est particulièrement fort dans ces régions, car l'eau souterraine est souvent la seule source d'eau, est vulnérable à la pollution et est sujette à la diminution. Quelques études concernent explicitement la recharge de nappes dans les régions tempérées et humides, parce que la recharge est normalement incluse dans les études régionales de nappes comme l'une des composantes du bilan hydrologique. La résolution des études régionales de bilan hydrologique en régions arides et semi-arides est au contraire souvent trop faible pour quantifier la composante limitée de recharge avec une précision suffisante.

Malgré de nombreuses études, la détermination des flux de recharge en régions arides et semi-arides reste pleine d'incertitudes. Les approches par traceurs multiples offrent probablement le meilleur potentiel pour fournir des résultats intéressants dans les études locales qui nécessitent une information localisée. Toutefois, de nombreux travaux indiquent que ces approches ne sont pas sans biais, parce que dans certains cas des écoulements préférentiels contribuent pour plus de 90% au total de la recharge estimée. Les résultats fournis par les traceurs (par exemple Cl^-, ^3H) doivent par conséquent être interprétés avec précaution dans les régions où existe un écoulement multi-modal dans la zone d'infiltration. De plus, l'estimation précise de l'apport total en chlorure est

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essentiel et le tritium peut être influencé par le transport de vapeur pour des flux faibles. En outre, les conditions paléoclimatiques et paléohydrologiques peuvent introduire des désaccords entre les processus actuels mesurés et les moyennes calculées sur le long terme.

Les écoulements fréquemment étudiés de recharge localisée et de variabilité spatiale ne sont pas un problème si l'intérêt est une estimation régionale. La clé pour les praticiens est l'objectif du projet, qui dicte s'il est approprié de recourir aux méthodes d'estimation localisée ou régionales basées sur la nappe. De nombreuses études indirectes de la recharge (wadi) fournies par la littérature sont particulières au site étudié; la relation entre les propriétés hydrauliques locales et les pertes le long des chenaux exige des recherches complémentaires.

Resumen A partir de mediados de 1980, se ha experimentado un notable aumento de referencias bibliográficas sobre estudios de recarga de acuíferos. Por tanto, es importante establecer qué se conoce actualmente y dar soporte a los técnicos encargados del desarrollo de recursos hídricos. Este artículo resume el conocimiento actual en lo que respecta a los procesos de recarga, identifica los problemas recurrentes en la evaluación de la recarga, e informa sobre algunos avances recientes en técnicas de estimación. Se enfatiza en regiones (semi-)áridas, ya que la necesidad de información es mayor en dichas áreas, donde las aguas subterráneas son a menudo la única fuente de agua, son vulnerables a la contaminación y existe riesgo de abatimiento de los niveles. Pocos estudios tratan de forma explícita la recarga en zonas templadas y húmedas, porque la recarga se incluye normalmente en las investigaciones a escala regional de las aguas subterráneas como una componente más del balance de agua. La resolución de los estudios regionales de balance de aguas en zonas (semi-)áridas, por el contrario, es a menudo demasiado baja para permitir una cuantificación suficientemente precisa de la recarga.

A pesar de los numerosos estudios existentes, la determinación de los flujos de recarga en regiones (semi-)áridas todavía presenta incertidumbres. Los métodos de trazadores múltiples ofrecen probablemente el mejor potencial para llegar a resultados fiables en estudios locales que requieren información 'puntual'. No obstante, muchos estudios indican que este enfoque no es directo, ya que el flujo preferente contribuye en algunos casos al 90% de la recarga estimada total. Los resultados obtenidos con trazadores (por ejemplo, cloruro, tritio) deben ser interpretados con precaución en áreas con flujo multimodal en la zona no saturada. Además, es esencial una estimación cuidadosa de la aportación total de cloruro, mientras que el tritio puede estar influenciado por transporte en forma de vapor a velocidades de flujo bajas. También, las condiciones paleoclimáticas y paleohidrológicas pueden dar lugar a discrepancias entre los procesos medidos en la actualidad y los valores calculados como promedios durante períodos largos.

Los conceptos frecuentemente estudiados de recarga localizada y variabilidad espacial no deben suponer un problema si lo que se busca son estimaciones a escala regional. Lo importante para los técnicos es el objetivo del proyecto, pues éste determina si se necesita métodos estimativos 'puntuales' o de mayor escala. Muchos estudios indirectos de recarga (wadis) referidos en la bibliografía son específicos del lugar; la relación entre las propiedades hidráulicas'puntuales' y las pérdidas en tramos de canales exige más investigación.

Keywords Groundwater recharge · Tracer studies · Groundwater development · Arid regions

Introduction

Groundwater use is of fundamental importance to meet the rapidly expanding urban, industrial, and agricultural water requirements, particularly in (semi-)arid zones. To quantify the current rate of groundwater recharge is thus a prerequisite for efficient and sustainable groundwater-resource management in these dry areas, where such resources are often the key to economic development. Recharge estimates should also be related to the aquifer targeted for development, which need not be the uppermost phreatic source.

Since the mid-1980s, a relative explosion of recharge studies has been reported in the scientific literature. Recognition of the growing need for reliable recharge estimation is also reflected in the active support by international agencies/non-government organizations (NGOs) and the publications that have emerged from various international meetings (e.g. Simmers 1988, 1997; Sharma 1989; Lerner et al. 1990; Bredenkamp et al. 1995).

Attention in this paper focuses principally on recharge of unconfined aquifers, often the most readily available and affordable source of water in (semi-)arid regions. These aquifers are also the most susceptible to depletion and contamination, with the recharge rate and dominant processes determining their level of vulnerability.

Aspects of Recharge

Recharge Types

The various sources of recharge to a groundwater system are well known. Principal recharge mechanisms from these sources have been conceptually defined by Lerner et al. (1990) as:

- *Direct recharge*: water added to the groundwater reservoir in excess of soil-moisture deficits and evapotranspiration by direct vertical percolation through the vadose zone.
- *Indirect recharge*: percolation to the water table through the beds of surface-water courses.
- *Localized recharge*: an intermediate form of groundwater recharge resulting from the horizontal (near-) surface concentration of water in the absence of well-defined channels.

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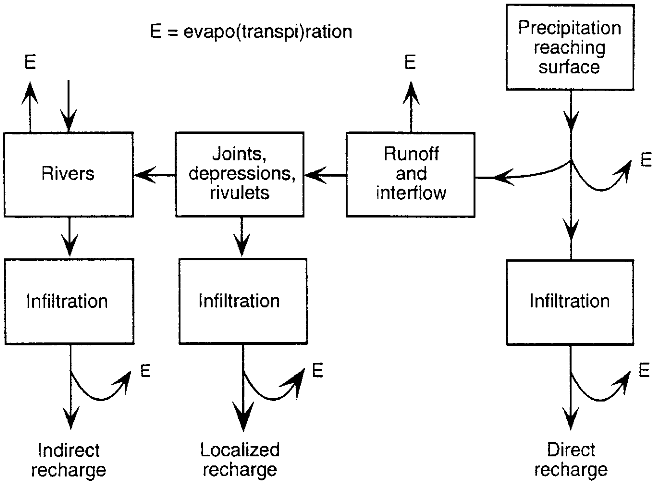

Fig. 1 The various mechanisms of recharge in a (semi-)arid area (Lerner 1997)

Figure 1 from Lerner (1997) is a simplified expression of these recharge mechanisms. In many locations, combinations of the various types occur, with percolation to a groundwater body by one or more of the following processes: (1) diffuse percolation, as either an unsaturated flux or a saturated front (piston-type flow); (2) macropore flow through root channels, desiccation cracks, and fissures; or (3) preferential flow caused by unstable wetting fronts and differentiated soil physical characteristics within the soil, notably between sandy and clayey sediments. A review of the literature indicates that recharge occurs to some extent in even the most arid regions and, as aridity increases, *direct* recharge is likely to become less important than *localized* and *indirect* recharge, in terms of total aquifer replenishment.

Recharge Processes

Recharge is defined in a general sense as the downward flow of water reaching the water table, forming an addition to the groundwater reservoir. One mechanism is downward percolation by soil water in excess of soil-moisture deficit and evapotranspiration (infiltration excess). This definition is rather straightforward, but several conceptual problems exist. Groundwater recharge over a certain area is normally considered to be equal to infiltration excess over the same area. However, not all this water necessarily reaches the water table. It might be hampered by low-conductivity horizons and disappear as interflow to nearby local depressions, where it runs off or evaporates instead of joining the regional groundwater system. Another problem might arise, especially in shallow aquifers in relation to areal scale, viz. a rise of the water table by recharge could initiate a local groundwater system with associated local seepage discharge within the considered area. The net recharge in that area is accordingly lower than the total downward flow to the table. A similar problem in areas with a high water table is associated with a time scale: water may initially join the groundwater reservoir but might subsequently be extracted by evapotranspiration.

Thus the chosen boundaries determine whether a local system is considered a part of the recharge flux or if temporary recharge is considered as part of the total long-term replenishment. A clear distinction should therefore be made, both conceptually and for any modelling purposes, between the potential amount of water available for recharge from the soil zone and the actual recharge reaching the water table. The term *potential* recharge was introduced by Rushton (1988). This type includes the above-mentioned excesses of precipitation over evapotranspiration, which subsequently disappear through a local discharge system or by evaporation from the saturated zone, but which could become 'permanent' recharge by lowering the water table after extraction. Moreover, lowering of a shallow water table can induce additional recharge by reducing evapotranspiration. This concept of *potential* recharge is important for modelling future conditions.

These conceptual problems normally do not occur in areas with deep water tables, far below the root zone. Under such conditions, virtually all water that passes the root zone is assumed to have escaped evapotranspiration and could recharge the groundwater reservoir. Average regional recharge over a longer period then equals average regional groundwater discharge. However, mechanisms exist that can cause soil water to ascend from considerable depths, notably under (semi-)arid conditions. Although these fluxes are usually very low, they may be significant in relation to downward percolation in arid regions. Coudrain-Ribstein et al. (1998), for example, report on stable-isotope studies that suggest fluxes of about 1 mm/year by capillary rise from (perched) water tables at a depth of about 20 m. Further, Adar et al. (1995) demonstrated the extraction of groundwater by a *tamarisk* tree in arid sand dunes from a depth of more than 15 m, and De Vries et al. (2000) detected extraction of water by deep-rooting *acacia* species from depths exceeding 50 m in the Kalahari desert. Physical confirmation of this deep extraction process is provided by a tracer-transport study on an alluvial fan in semi-arid Spain for the shrub species *Retama sphaerocarpa* [tracer injection depths 16 and 28 m; Haase et al. (1996)].

Vapour transport is another mechanism that produces a considerable flux in situations with a temperature gradient. De Vries et al. (2000) measured an average seasonal temperature difference of 4 °C in the Botswana Kalahari sand beds between the root zone (at 3 m) and a depth of 7 m. This gradient is caused by a phase lag in the seasonal temperature cycle of half a year, and it produces an upward vapour transport during the winter and a downward transport during summer of about 0.2–0.3 mm per season. These mechanisms thus cause an imbalance between percolation below the (shallow) root zone and actual recharge, and/or between actual recharge and total discharge flux. Moreover, large groundwater systems with low fluxes and long relaxation time are often not in a steady state. These systems therefore usually

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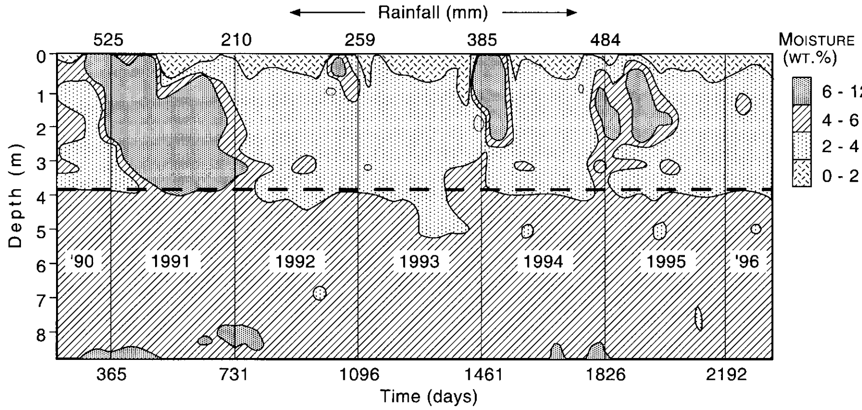

Fig. 2 Time series of seasonal moisture distribution in Kalahari sand, based on neutron-probe observations. *Dashed line* indicates approximate root zone depth. (After Beekman et al. 1999)

contain residual components of hydraulic head and hydraulic gradient from paleoclimatic conditions on a time scale of thousands of years, causing an imbalance between recharge and discharge. An example of the latter situation is groundwater that feeds oases in large depressions of the Egyptian western desert (Burdon 1977). This groundwater, more than 10,000 years old, originates from earlier pluvial periods; the relatively low flux-storage ratio in these huge aquifers enables water to flow for tens of thousands of years.

The interaction of climate, geology, morphology, soil condition, and vegetation determines the recharge process. In general, groundwater recharge in (semi-)arid areas is much more susceptible to near-surface conditions than in more humid regions. Deep percolation in humid areas is mainly controlled by the potential precipitation surplus (rainfall minus potential evapotranspiration), the infiltration capacity of the soil, and the storage and transport capacity of the sub-surface. In (semi-)arid areas, however, potential evapotranspiration on average exceeds rainfall, so that groundwater recharge particularly depends on rainfall events of high concentration, accumulation of rain water in depressions and streams, and the ability of rain water to escape evapotranspiration by rapid percolation through cracks, fissures, or solution channels. Recharge is normally hampered by thick alluvial soils, which allow high retention storage during the wet season and vegetation that subsequently extracts soil water in the next dry season. In contrast, a poor vegetation cover on a permeable soil or a fractured porous bedrock near the surface, together with high-intensity rainfall, create favourable conditions for recharge.

Influence of Lithology and Geomorphology

The influence of lithology and geomorphology in semiarid areas is illustrated in Botswana by differences between the Kalahari sands and adjoining Precambrian hard-rock area (Gieske 1992; De Vries 1997; Selaolo 1998; De Vries et al. 2000). The moderate average annual rainfall of 250–500 mm supports a rather dense vegetation, which classifies the Kalahari as a bush and tree savannah with alternating grass steppe. High infiltration capacity, combined with high retention storage in the Kalahari sand during the summer wet season and subsequent high evapotranspiration by dense vegetation during the dry season dictate that little water passes the root zone to contribute to aquifer recharge. Environmental-tracer studies and groundwater flow modelling indicate that recharge is about 5–10 mm/year in the fringe area, where rainfall is about 450 mm, to less than 1 mm/year in the central Kalahari, where rainfall is about 350 mm. Figure 2 indicates soil-water dynamics in the Kalahari under uniform sand conditions. Significant soil-water exchange occurs in the root zone, with only minor percolation below this zone. The sharp boundary at the root-zone base reflects the marked influence of moisture content on hydraulic conductivity. Higher recharge rates occur in local depressions, notably in situations where water infiltrates rapidly through fractured duricrust horizons (Fig. 3).

Recharge in the Botswana Precambrian area is largely restricted to fractured zones that form groundwater basins that are about 5–10 km^2 in area. In many places, these zones coincide with morphological depressions or ill-defined dry valleys. Average areal recharge in the basins, where mean annual rainfall is 500–550 mm, ranges from 10 mm/year through alluvial loamy sediments to 30 mm/year through coarse-grained sediments and fractured outcrops. Several studies in areas that have even more arid conditions (average rainfall less than 200 mm/year) indicate that regional recharge of a few millimetres per year is not uncommon in areas with a coarse-grained soil or fractured-rock outcrops (see Issar and Passchier 1990). Both the Kalahari and the Precambrian areas are characterized by multi-modal water fluxes in the vadose zone. Preferential flow contributes on average ~50% of the estimated total recharge, though values as high as 70–90% are known. Recharge induced by minor topographic variations is also important at a local scale. Gieske et al. (1990) observed horizontally concentrated infiltration into rills and lateral soil-water movement toward intervening ridges. Soil water below the rills has low salt content, whereas that below the ridges has higher concentrations, because of enrichment by enhanced evapotranspiration. These rills and ridges

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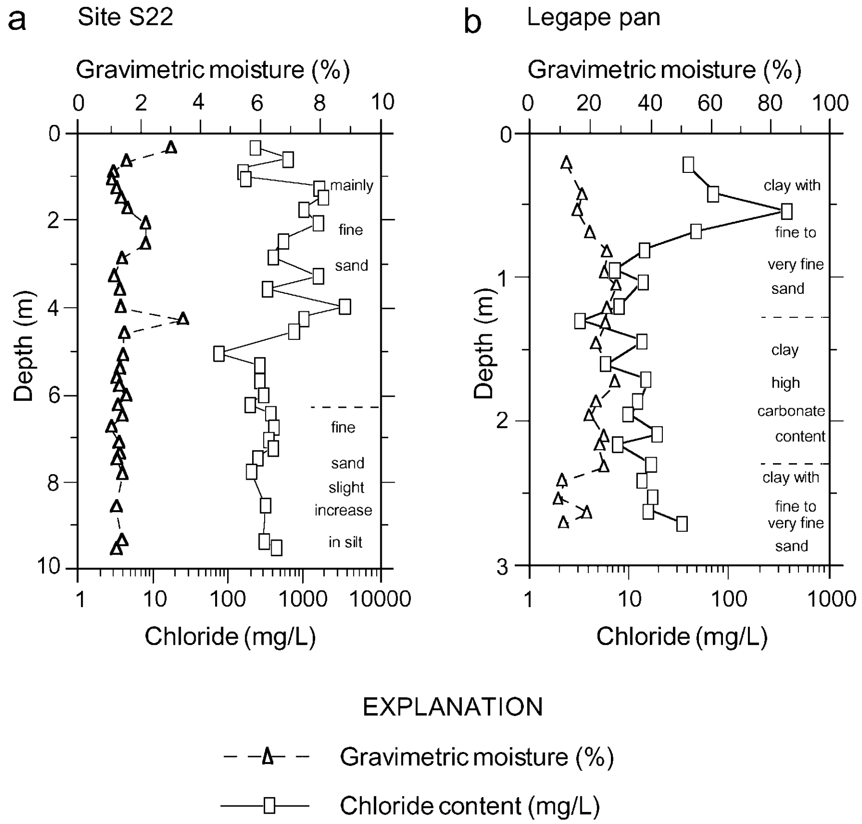

Fig. 3 Vertical soil-moisture and chloride profiles for **a** a level site (S22) and **b** Legape pan in the Letlhakeng-Botlhapatlou sand area at the fringe of the Botswana Kalahari. Average rainfall: 450 mm/year; calculated recharge at S22: ~2 mm/year; calculated recharge at Legape pan: ~30 mm/year (De Vries et al. 2000)

form undulations less than 1 m high and tens of metres wide.

Karst is often highly effective in enhancing recharge. Hoetzl (1995), for example, reports on an exposed karst area in Saudi Arabia where 47% of the average rainfall (93 mm/year) disappears into sinkholes and corrosionally extended joints. Another example of enhanced recharge from a combination of climate and sub-surface conditions is demonstrated by Mediterranean limestone areas, where high-intensity winter precipitation infiltrates exposed karst surfaces. These conditions account for the excellent aquifers in the Portuguese Algarve, where annual recharge is estimated to be 150–300 mm in areas that have alternating karstified dolomites and marls and a climate that is characterized by hot, dry summers and an average annual rainfall of only 550 mm (De Vries and Schwan 2000). Similar values are reported by Issar and Passchier (1990) for limestone aquifers in that part of Israel that has a Mediterranean climate. Some basalt plateaus also have high levels of surface fracturing and weathering, thus facilitating high recharge rates. Under (paleo-)humid conditions, however, basalt weathering sometimes produces black cotton soils, which hamper infiltration because of swelling clays.

Recharge Estimation

Differences in groundwater recharge sources and processes mean that the applicable value of available estimation techniques varies. Although *direct* recharge is known to be of decreasing significance with increasing aridity, the processes are conceptually the easiest to define, and they still form the basis of numerous recharge-estimation techniques in common use. Transient aspects, such as the actual frequency of recharge events and the transit time until recharge takes place, are also important in this respect.

Procedures used to quantify recharge from the various sources (i.e. direct measurement, water-balance methods, Darcian approaches, tracer techniques, and empirical methods) and many of the problems encountered with each are addressed by Gee and Hillel (1988), Lerner et al. (1990), Allison et al. (1994), Stephens (1994), Lerner (1997), and Simmers (1997), among others. Summary comparisons of the various methods are offered by Lerner et al. (1990), Bredenkamp et al. (1995), and Stephens (1996).

Few water-resource studies in humid areas are explicitly concerned with groundwater recharge. Recharge usually forms one of the components in an overall water balance, and inaccuracies in the water-balance determination are normally sufficiently small, in comparison with the magnitude of the recharge component, to allow for a reasonable estimate. Alternatively, one can determine recharge through the vadose zone from direct calculation of water fluxes, either by applying environmental tracers or by establishing a vadose-zone water balance on the basis of soil, climate, and vegetation data. Examples are offered by Johansson (1987), Saxena (1987), Meinardi (1994), and Gehrels (1999). In arid and semi-arid cli-

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mates, however, the latter method is not always straightforward, because the small recharge amount calculated from the difference between rainfall and actual evapotranspiration (E_a) is normally less than the accuracy range of E_a determination.

The problem with Darcy's law solutions for water movement in the vadose zone is that they require knowledge of the soil-water retention curves and unsaturated hydraulic-conductivity curves. Direct determination of these is difficult. However, indirect methods for estimating soil hydraulic properties have been developed from readily-measured soil data, and these methods often yield sufficiently precise information for many practical applications without increasing costs (see Sophocleous and Perry 1985; Rawls et al. 1991; Van Genuchten et al. 1992; Hendrickx and Walker 1997). Lumped-parameter percolation models have also proven useful. The Van der Lee and Gehrels (1997) EARTH model, for example, makes use of E_a estimates and simplified transport models for percolation through the vadose zone; the model is calibrated by groundwater-level fluctuations, taking into account the groundwater recession component. Other vadose-zone models with recharge applications are illustrated by Beverly et al. (1999), Zhang et al. (1999), and Gehrels (2000). Such models are especially interesting for seasonal or interannual recharge-fluctuation monitoring via groundwater-level observations. Groundwater levels are also a key input to groundwater flux and volume-change considerations at the basin scale; examples are given by Bredenkamp et al. (1995) and Ketchum et al. (2000).

Tracer methods have several advantages over physical techniques. One advantage is that the precision of a recharge estimate does not decrease as the moisture flux to groundwater decreases. Many tracer studies in (semi-)arid areas are based on ^3H or Cl^- profiles in the vadose zone. The methods are conceptually simple, though problems arise with ^3H vapour transport when recharge is less than 20 mm/year (Cook and Walker 1995) and in determining the atmospheric Cl^- input. With regard to Cl^- deposition, 8 years of sampling in the Kalahari using standard rain gauges indicates a high areal and temporal variation (Selaolo 1998). A further complicating issue is created by tree canopies, which capture and enhance dry aerosol deposition. Other tracers used in recharge studies are the stable isotopes ^{18}O and ^2H. These isotopes are useful for identifying processes and origin of the water, but pose difficulties in quantitative recharge estimates because they are not conservative and are subject to fractionation by evaporation. Examples of stable-isotope applications to recharge estimation are presented by Allison et al. (1984), Saxena (1987), and Gehrels et al. (1998). Allison et al. (1984) made use of the downward decrease in heavy-isotope concentration through dilution by percolating rain water in semi-arid Australia. Saxena (1987) and Gehrels et al. (1998) used the distinct seasonal isotope signal to trace and model vertical moisture fluxes in the temperate, humid climates of Sweden and The Netherlands, respectively.

In conclusion, groundwater-recharge estimation is an iterative process. The water-resource practitioner should note that:

- Realistic estimation depends on first identifying important features influencing recharge for a given locality and probable flow mechanisms relating to the aquifer targeted for development.
- It is desirable to apply and compare multiple independent approaches.
- Model development is too often seen as an alternative to field work, and the model applied must be appropriate to actual field conditions.
- For (semi-)arid groundwater systems with a large relaxation time, a residual head or hydraulic gradient is likely to exist from paleoclimatic conditions.

Some Challenges in Estimating Recharge

Groundwater recharge has been repeatedly shown to be highly variable; the greater the aridity, the smaller and potentially more variable the natural flux. In addition to the perennial difficulties associated with sparse information, particularly in (semi-)arid areas, various general recharge estimation 'problems' recur, on the basis of a review of the literature to the late-1990s. These include: (1) variability of recharge in time and space [e.g. effects of climatic and land-use changes on tracer profiles/mass balances; the spatial extrapolation of 'at-point' data; determination of reliable (representative) water-balance parameters]; (2) the assessment and regional hydrological consequences of *localized* and *indirect* recharge; and (3) the impacts of urban development on groundwater recharge.

A scan of the more recent literature shows that not all these 'problems' have been satisfactorily resolved. Equally evident, however, is that considerable progress has been made. This paper addresses some of the above challenges and outlines recent developments within each. Particular attention is accorded to recharge space/time variability, land-use change, and the *indirect*/*localized* components. Foster et al. (1994) and Chilton (1997, 1999) present details on the impacts of urban development on recharge.

Variability of Recharge with Time

Variations in groundwater recharge with time are well documented. Figure 4 offers an example from Botswana, based on historical daily rainfall records, which were converted into recharge values by semi-empirical rainfall-recharge relations established from the lumped-parameter EARTH model (Gieske 1992). Comparable results were obtained by Bredenkamp (1988) for Wondergat sinkhole, just south of Botswana, using a 34-year water-level observation record.

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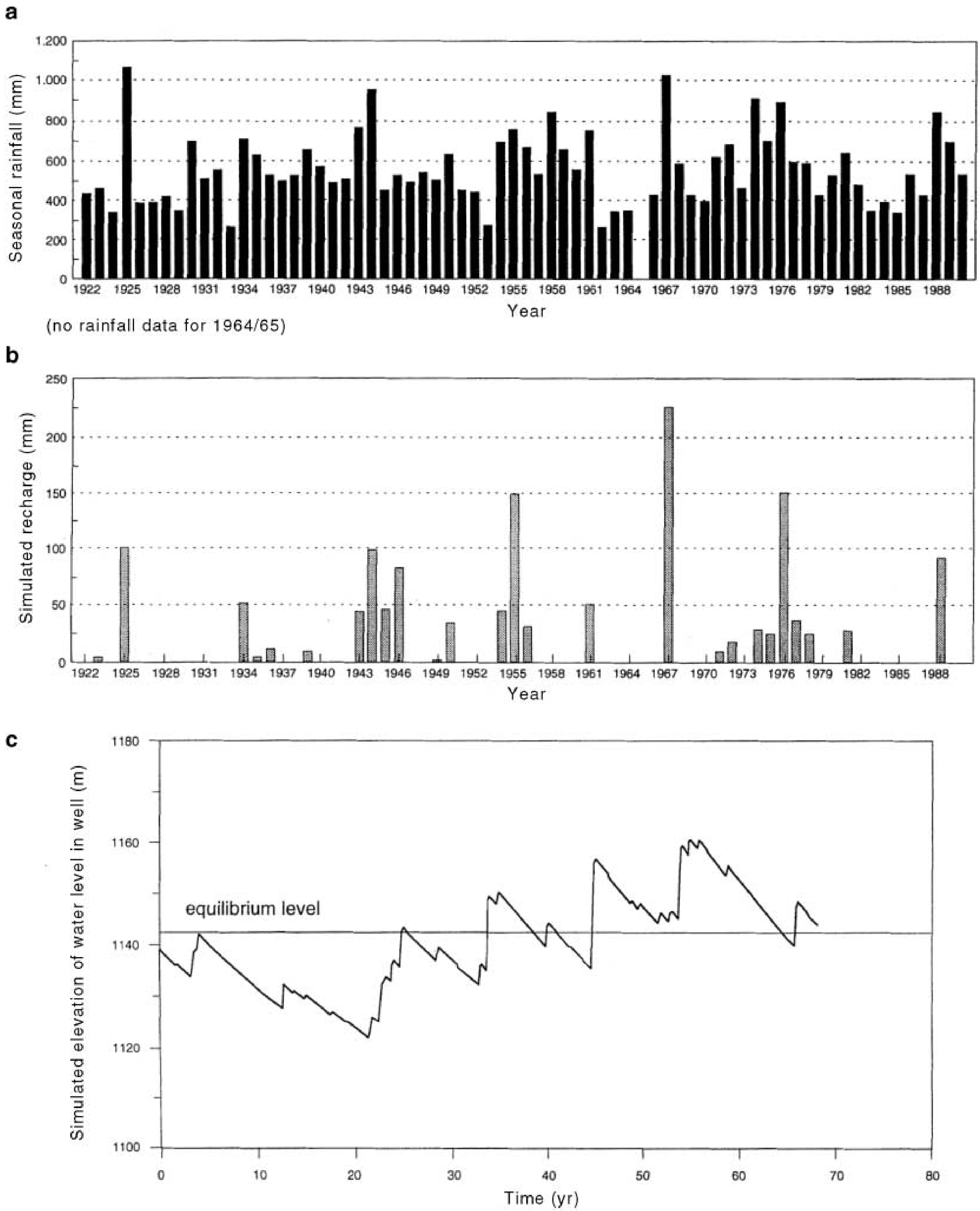

Fig. 4a–c Recharge time series, 1922–1990, simulated using the EARTH model and Lobatse (Botswana) daily rainfall records. **a** Seasonal rainfall; **b** simulated recharge; **c** simulated water level in well (Gieske 1992)

An implication from such studies is that when significant recharge results from only infrequent large events, it is highly misleading to describe mean annual recharge or recharge as a proportion of mean annual rainfall. The

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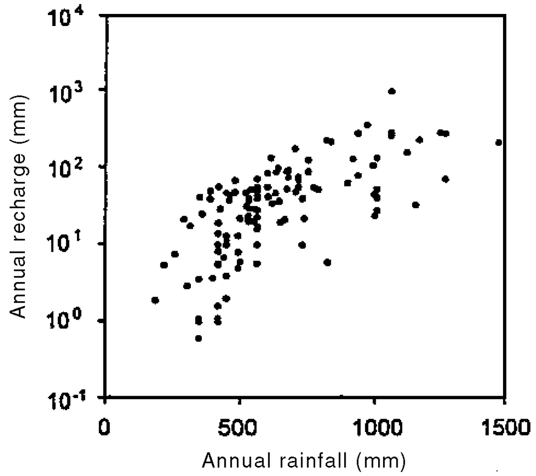

Fig. 5 Recharge data from South Africa, Botswana, and Zimbabwe, plotted as a function of annual rainfall (Selaolo 1998)

danger of such a simplistic approach is illustrated by comparing results from Botswana, South Africa, and Zimbabwe (Fig. 5); the diagram shows that recharge varies by a factor of up to 100 for the same annual rainfall. These data include areas with different lithology and morphology and are partly from spring data, for which the contributing area is not always clear. However, in most of the areas, regional recharge is very low where rainfall is less than 400 mm/year.

Estimation of Regional Recharge

Numerous studies have shown that very reasonable estimates of recharge over extended areas can be derived using readily obtained field data, without considering the complicating aspects of small-scale (local) variability. Methods include regional-flux determination by isotope dating, chloride mass-balance calculations, tracer mixing-cell modelling, Darcian flow modelling, and direct measurements of spring discharge or stream baseflow. Examples of relatively low-cost investigations are provided by Adar et al. (1988), Gieske and De Vries (1990), Athavale et al. (1992), Edmunds and Gaye (1994), Kennett-Smith et al. (1994), Bredenkamp et al. (1995), Leaney and Herczeg (1995), Sukhija et al. (1996), Birkle et al. (1998), and Rangarajan and Athavale (2000).

Selaolo (1998), Beekman et al. (1999), and Chen Zhu (2000) also illustrate that geochemical and isotopic (^{14}C, ^{4}He) tracers in the saturated zone provide attractive alternative approaches for estimating recharge. These studies utilized an areal integration of long-term average tracer inputs, therefore circumventing the complexities resulting from diverse recharge pathways. The long-term average areal recharge rate from the $^{3}He/^{4}He$ ratio method is shown by Selaolo (1998) to be in the same order of magnitude as values obtained by chloride mass balance and groundwater flow modelling. These $^{3}He/^{4}He$ and ^{14}C methods are not problem free, however, because both tracers generally interact with the aquifer medium. Atmospheric ^{14}C mixes with carbon produced from limestone with zero ^{14}C in the aquifer, and the use of ^{4}He is based on its production by the aquifer material, with a possible inflow component from the mantle. Additional difficulties occur as a result of dispersion and when stagnating zones are present. Very old water beyond the dating limits of ^{14}C can be dated with ^{36}Cl. For example, this technique has been applied in the Australian Great Artesian Basin, where groundwater ages are >100,000 years (Torgersen et al. 1991).

Other recent methods used to estimate recharge over large areas reflect a statement in Lerner et al. (1990, p 14) that "potential lies in a combination of field measurements and remote sensing." Examples of this approach are provided by Sophocleous (1992), Salama et al. (1994b), and Hutjes (1998). Results indicate that despite its present shortcomings, the areal water-balance method is a powerful tool to understand the main features of recharge processes, if short time steps are used and the spatial variability of components is taken into account.

One should realize, however, that these regional recharge estimates are often based on the assumption that average recharge equals the average discharge. This condition does not apply where the hydraulic-gradient relaxation time is long compared with changing conditions, which is often the case in (semi-)arid areas for very large groundwater basins with a low flux-storage ratio. Under such conditions, groundwater head gradients and associated flow could be residual (Burdon 1977; De Vries 1984, 1997; Tyler et al. 1996; Corbet 2000; De Vries et al. 2000). Geochemical and isotopic studies from the saturated zone can reveal these paleo-recharge events. Dabous and Osmond (2001), for example, identified the different water sources and their mixing volumes in the Nubian aquifer, Egypt, using uranium isotopes. Further, in a study of the Libyan desert, Edmunds and Walton (1980) were able to differentiate groundwater from regional pre-Holocene recharge and locally recharged water from 5,000–7,800 years B.P.

Recharge and Land-Use Change

Many early attempts to estimate recharge in situations involving land-use change have generally assumed that evapotranspiration and precipitation are the only time-variant factors affecting the various processes. However, a problem occurs when transit time until recharge is long and land-use changes are known to have occurred in an area prior to current data-collection programs. In such cases, the hydrological system is in a state of dynamic evolution; examples are cited by Allison et al. (1994), Phillips (1994), and Bromley et al. (1997). The Australian studies, in particular, illustrate the crucial influence of vegetation on recharge in semi-arid areas through historical evapotranspiration changes. Significantly increased recharge resulted from removal of the indigenous vegetation in large parts of southeastern Australia more than 100 years ago. The effect is a rise in water ta-

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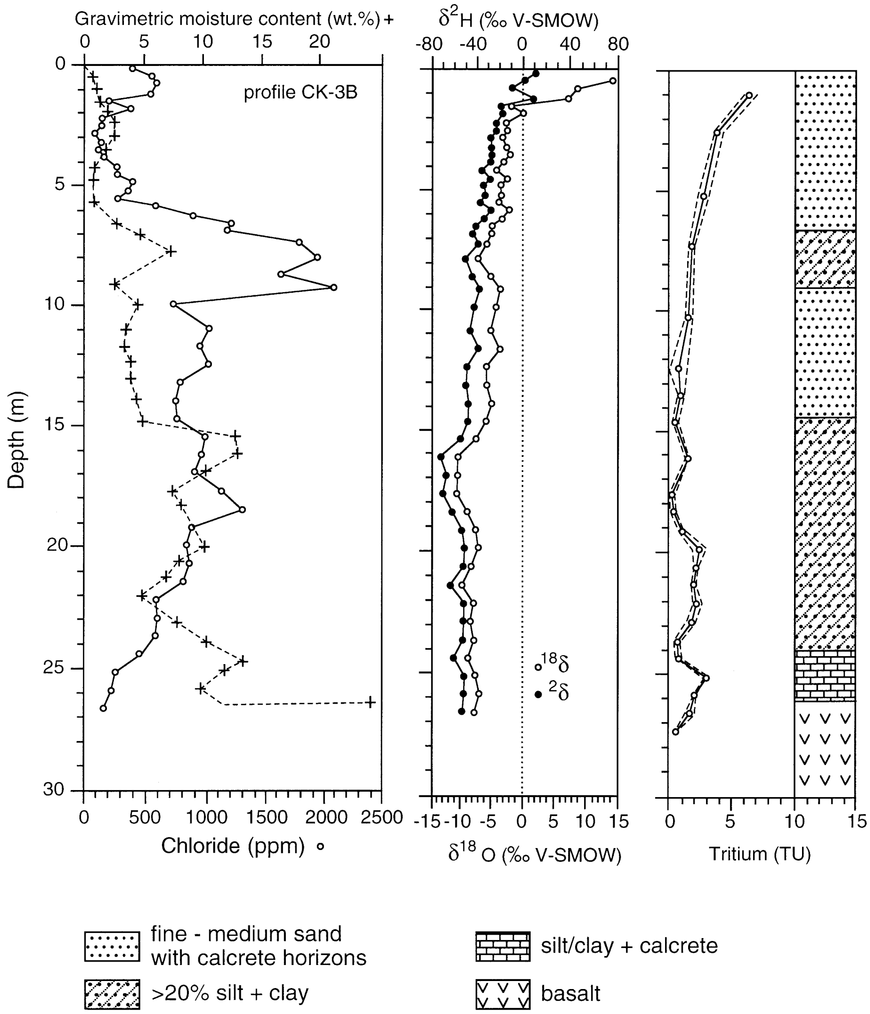

Fig. 6 Central Kalahari (Botswana) tracer profiles from a deep borehole; average rainfall: ~350 mm/year (Beekman et al. 1999)

bles and associated problems of widespread salinization (Allison et al. 1990). A further illustration of the role of vegetation is in southwestern Niger (Sahel) where, as a result of land-use change, an increase in recharge from a previous 5 mm/year to the present 20 mm/year has induced a long-term water-table rise (Leduc et al. 2001). Clearing of vegetation changed the hydraulic properties of the topsoil, which in turn increased surface runoff, concentrated water in depressions, and resulted in enhanced recharge.

Apart from direct water-level measurements, estimates of changes in recharge resulting from land-use change usually involve analyses of 'at-point' Cl^- profiles, which typically display complex shapes under non-steady state conditions. An example of this approach is the study by Walker et al. (1991) using a combination of tracer (Cl^-) and physical (suction profile) methods. The procedure remains valid even where the chloride profiles are distorted. The method also allows an estimate to be made of the probable time delay before the effects of land-use change reach the water table.

Estimation of Localized Recharge

Recharge along preferential flow paths has received considerable attention in the past decade, with an increasing number of studies verifying the significance of the process and attempting to quantify its relative contribution to the groundwater body. The literature also indicates that in some cases local groundwater-recharge models that ignore the possibility of such phenomena may be highly misleading. An overview of the topic is given by Stephens (1994).

Gee and Hillel (1988) visualize *localized* recharge occurring on three spatial scales: (1) micro-scale pathways, several centimetres or decimetres apart, such as those formed by shrinkage cracks, roots, and burrowing animals; (2) meso-scale flow paths, with a spacing of several metres or tens of metres, initiated by local topographic or lithological variations; and (3) macro-scale flow paths, spaced several hundred (or more) metres apart, caused by major landscape features, such as karst sinks or playa basins. Such variations in local recharge have been demonstrated and quantified for many soil types. Typical examples are presented by Gieske (1992), Scanlon (1992), Hoetzl (1995), Nativ et al. (1995), Wood and Sanford (1995), Herczeg et al. (1997), Scanlon and

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Goldsmith (1997), Wood et al. (1997), Selaolo (1998), Beekman et al. (1999), Gehrels (1999, 2000), and Scanlon et al. (1999). All used isotope- and/or chemical-tracer techniques to solve their specific problem. The examples of Hoetzl (1995), Wood et al. (1997), and Scanlon et al. (1999) address both surface 'runon' and spatially variable vertical fluxes. Research by Wood et al. (1997) has a regional perspective, though much of the effort focuses on recharge processes in and around ephemeral playa lakes. Results show that 15–35% of total recharge of 11 mm/year on the Texas and New Mexico High Plains, USA, occurs as piston flow through playa basin floors that occupy only 6% of the area. The remaining recharge, from 94% of the area, comes from macropore flux near the basin floors (60–80%) and diffuse infiltration over the region (~5%).

By way of further example, Fig. 6 presents tracer results from a deep borehole in the central Kalahari (Beekman et al. 1999; De Vries et al. 2000). Chloride concentration decreases dramatically below 9 m, suggesting preferential flow in this area with an average areal recharge of less than 1 mm/year. This conclusion is supported by the higher ^{3}H pulses (~3 tritium units) observed at lower levels in the borehole.

An alternative approach to solving the variability problems inherent in estimating *localized* recharge is the combination of frequency-domain electromagnetic (EM) measurements and 'at-point' Cl^{-} mass balances. The method is not new conceptually, but some recent studies have shown promise (e.g. Cook et al. 1992; Salama et al. 1994a; Scanlon et al. 1999).

The problems relating to *localized* recharge need to be kept in perspective, however. If concern is with acquiring recharge estimates over a limited area (e.g. for waste-disposal or local water-supply purposes), then the need for detailed information is evident. In this situation, multiple 'at-point' investigations are appropriate, with identification of the preferential flow contribution a prerequisite. Conversely, for projects on a regional scale, or those requiring only preliminary recharge estimates, area- or groundwater-based methods, as detailed above, are relevant, and small-scale spatial variability ceases to be an issue (Simmers 1998).

Estimation of Indirect Recharge

The two principal mechanisms of natural groundwater recharge under conditions of ephemeral flow are mountain-front and channel recharge. In (semi-)arid regions, both types frequently occur in the same drainage basin and are difficult to separate in practice. Descriptions of their respective physical and hydrological characteristics are given by Lerner et al. (1990), Kruseman (1997), and Lerner (1997).

With respect to mountain-front recharge, qualitative measures of the seasonal distribution and origins of recharged water are derived from chemical- and isotope-tracer sampling of spring and well water, precipitation, and runoff (see Gieske 1992; Cook and Solomon 1997; Girard et al. 1997; Clark et al. 1998; Cunningham et al. 1998). Quantitative estimation of the surface-runoff component is possible by the water-balance method, but the sub-surface flow is difficult to isolate. One solution is to estimate the total by a Darcy throughflow calculation within the main aquifer, away from the mountain boundary (Lerner 1997). An alternative approach is proposed by Chavez et al. (1994a, 1994b), who developed and tested an analytical, seasonal, streamflow model that includes mountain-front recharge as one of the parameters. The model is formulated in terms of parameters with physical significance, makes use of normally recorded climatic/hydrometric data, and favours remotely sensed input of basin characteristics.

The more recent studies to determine recharge from wadis have utilized water-balance methods, empirical formulae, isotope-tracer techniques, and Darcian approaches. None is straightforward, and the empirical formulae, in particular, are site specific. Detailed examples are provided by Abdulrazzak et al. (1989), Hughes and Sami (1992), Parissopoulos and Wheater (1992), Sorman and Abdulrazzak (1993, 1997), Scanlon (1994), Lange et al. (1997, 1999), Sorman et al. (1997), El-Hames and Richards (1998), Sharma and Murthy (1998), Ponce et al. (1999), and Shentsis et al. (1999). Most target the unsaturated response of wadi alluvium under field conditions and require an intensive data-collection program. Also evident is that river-bed infiltration often decreases in the course of a flood event due to silt deposition. With the possible exception of the Tabalah (Saudi Arabia) investigations, few studies address the issue of spatial heterogeneity in bed material. Thus the relationship between 'at-point' hydraulic properties and channel-reach transmission losses needs further investigation.

Concluding Remarks

Limitations are associated with the well-established recharge-estimation methods, most of which yield results that are problem and scale dependent. Practitioners are encouraged to explore the more recent techniques identified here. A note of caution, however: many of the reported studies are in response to specific local issues and are not necessarily reliable for general application. Estimation of groundwater recharge is an iterative process, involving progressive aquifer-response data collection and resource evaluation. Field measurements are a necessary component of a recharge investigation, because they are the only means to realistically determine recharge processes. A principal criterion for all models is that they must represent the essential features of any flow mechanisms. Recharge is not only highly dependent on climate, but also on surface and sub-surface conditions, which do not always reflect lithology and a currently dry climate. Regolith, duricrust, exposed karst, and the formation of secondary permeability and subsequent aquifer development depend on geological history, including paleoclimatic and paleohydrological evolution, and are generally unique for a particular region.

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Multiple tracer approaches probably offer the best potential for reliable recharge estimates in studies that require 'at-point' information, though data must be interpreted with care in areas with multi-modal flow in the vadose zone. The issues of *localized* recharge and spatial variability need not be a problem if concern is with regional estimates. The key for practitioners is the project objective, which dictates whether multiple 'at-point' or area-/groundwater-based estimation methods are appropriate. The combination of reliable local data, remote sensing, and GIS technology offers promise for a better understanding and quantification of recharge over large areas.

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