HYDROLOGICAL PROCESSES
Hydrol. Process. **20**, 3335–3370 (2006)
Published online in Wiley InterScience
(www.interscience.wiley.com) DOI: 10.1002/hyp.6335

Global synthesis of groundwater recharge in semiarid and arid regions

Bridget R. Scanlon,[1]* Kelley E. Keese,[1] Alan L. Flint,[2] Lorraine E. Flint,[2]
Cheikh B. Gaye,[3] W. Michael Edmunds[4] and Ian Simmers[5]

[1] *The University of Texas at Austin, Bureau of Economic Geology, Jackson School of Geosciences, Austin, TX, 78713-8924, USA*
[2] *US Geological Survey, Sacramento, California 95819-6129, USA*
[3] *Université Cheikh Anta Diop, Département de Géologie, Dakar, Senégal*
[4] *Oxford Center for Water Research, Oxford University Center for the Environment, Oxford OX1 3QY, UK*
[5] *Vrije Universiteit, Faculty of Earth- and Life Sciences, Amsterdam, The Netherlands*

Abstract:

Global synthesis of the findings from ∼140 recharge study areas in semiarid and arid regions provides important information on recharge rates, controls, and processes, which are critical for sustainable water development. Water resource evaluation, dryland salinity assessment (Australia), and radioactive waste disposal (US) are among the primary goals of many of these recharge studies. The chloride mass balance (CMB) technique is widely used to estimate recharge. Average recharge rates estimated over large areas (40–374 000 km^2) range from 0·2 to 35 mm $year^{-1}$, representing 0·1–5% of long-term average annual precipitation. Extreme local variability in recharge, with rates up to ∼720 m $year^{-1}$, results from focussed recharge beneath ephemeral streams and lakes and preferential flow mostly in fractured systems. System response to climate variability and land use/land cover (LU/LC) changes is archived in unsaturated zone tracer profiles and in groundwater level fluctuations. Inter-annual climate variability related to El Niño Southern Oscillation (ENSO) results in up to three times higher recharge in regions within the SW US during periods of frequent El Niños (1977–1998) relative to periods dominated by La Niñas (1941–1957). Enhanced recharge related to ENSO is also documented in Argentina. Climate variability at decadal to century scales recorded in chloride profiles in Africa results in recharge rates of 30 mm $year^{-1}$ during the Sahel drought (1970–1986) to 150 mm $year^{-1}$ during non-drought periods. Variations in climate at millennial scales in the SW US changed systems from recharge during the Pleistocene glacial period (≥10 000 years ago) to discharge during the Holocene semiarid period. LU/LC changes such as deforestation in Australia increased recharge up to about 2 orders of magnitude. Changes from natural grassland and shrublands to dryland (rain-fed) agriculture altered systems from discharge (evapotranspiration, ET) to recharge in the SW US. The impact of LU change was much greater than climate variability in Niger (Africa), where replacement of savanna by crops increased recharge by about an order of magnitude even during severe droughts. Sensitivity of recharge to LU/LC changes suggests that recharge may be controlled through management of LU. In irrigated areas, recharge varies from 10 to 485 mm $year^{-1}$, representing 1–25% of irrigation plus precipitation. However, irrigation pumpage in groundwater-fed irrigated areas greatly exceeds recharge rates, resulting in groundwater mining. Increased recharge related to cultivation has mobilized salts that accumulated in the unsaturated zone over millennia, resulting in widespread groundwater and surface water contamination, particularly in Australia. The synthesis of recharge rates provided in this study contains valuable information for developing sustainable groundwater resource programmes within the context of climate variability and LU/LC change. Copyright © 2006 John Wiley & Sons, Ltd.

KEY WORDS groundwater recharge; water resources; climate variability; land use/land cover change

Received 5 July 2005; Accepted 1 March 2006

* Correspondence to: Bridget R. Scanlon, The University of Texas at Austin, Bureau of Economic Geology, Jackson School of Geosciences, Austin, TX, 78713-8924, USA. E-mail: bridget.scanlon@beg.utexas.edu

INTRODUCTION

Increasing demands on limited water supplies in semiarid and arid [(semi-) arid] regions result in a critical status of groundwater recharge. (Semi-) arid regions are expanding and represent 30% of global terrestrial surface area (Dregne, 1991). Currently, an estimated 1·1 billion of the 6 billion world population lacks access to sources of clean drinking water (WHO, 2003). Water scarcity will become more critical in the future as population growth in (semi-) arid regions surpasses that in more humid settings. For example, population in Sub-Saharan Africa was one-third that of China in 1950, one-half in 2002, and is projected to surpass it in 2050 (US Census Bureau, 2004). Approximately 40% of the US population growth between 1960 and 2000 occurred in (semi-) arid states in the SW US (US Census Bureau, 2004). Surface water resources are generally scarce and highly unreliable in (semi-) arid regions, with the result that groundwater is the primary source of water in these regions. The International Atomic Energy Agency (IAEA) estimates that much of the groundwater being developed in (semi-) arid regions is fossil water and is not sustainable. Sustainable management of these aquifers to meet human and ecosystem needs will require accurate estimates of groundwater recharge.

Recharge has been estimated in (semi-) arid regions using a variety of techniques, including physical, chemical, isotopic, and modelling techniques. These techniques have been described in previous studies and reviews (Lerner *et al*., 1990; Hendrickx and Walker, 1997; Zhang and Walker, 1998; Kinzelbach *et al*., 2002; Scanlon *et al*., 2002). The purpose of recharge studies has dictated to some extent the method used to estimate recharge and the scale of the studies. Regional recharge estimation for water resources evaluation has relied mostly on groundwater-based approaches, which integrate over large spatial scales and generally cannot be used to estimate local variability in recharge. In contrast, recharge estimation for water quality studies focusses on spatial variability in recharge, which is critical for contaminant transport.

Various reviews of recharge have been conducted in the past, focussing primarily on (semi-) arid regions. Simmers (1988) edited a volume on recharge that focusses primarily on techniques for estimating recharge and provides applications and case studies in (semi-) arid regions. Papers from a symposium on groundwater recharge that was held in Australia in 1987 are compiled in an edited volume by Sharma (1989) and describe various techniques for estimating recharge, emphasizing recharge processes and mechanisms on the basis of data from Australia. The International Association of Hydrogeologists published a volume on recharge edited by Lerner *et al*. (1990) that includes descriptions of recharge in different hydrogeologic settings. A compilation of papers by IAEA (2001) providing valuable information on recharge in water-scarce areas is based on field studies that estimate recharge at 44 benchmark sites. These studies showed that rainfall below 200 mm usually results in negligible recharge. A special volume of the *Hydrogeology Journal* devoted to recharge includes papers on recharge processes and methods of estimating recharge, including remote sensing, ground-based and modelling approaches, artificial and urban recharge, and case studies in (semi-) arid regions (Scanlon and Cook, 2002). Recharge issues related to the SW US are described in Hogan *et al*. (2004), which includes papers on recharge mechanisms, processes, and case studies. Recharge in the SW US is also the focus of a USGS professional paper (Stonestrom and Leake, in press), which describes the climatic and geologic framework and provides information on methodologies and case studies on regional and focussed recharge. Although there are many reviews of recharge studies in (semi-) arid regions, none of the existing reviews compiles recharge estimates from studies on a global scale. Such information is important for comparison with global scale models (e.g. Doll *et al*., 2003).

The purpose of this paper was to synthesize recharge estimates for (semi-) arid regions globally to evaluate recharge rates, controls, and processes and to assess the impacts of climate variability and land use/land cover (LU/LC) changes on recharge. The compilation emphasizes regional recharge estimates, where available, which are important for water resources. The baseline data provided in this compilation will be a valuable resource for comparison with future model estimates of recharge based on regional and global scale models. Synthesis of recharge rates from different studies provides valuable insights into recharge processes and controls and is essential for developing sustainable water resource management plans in (semi-) arid regions within the context of climate variability and LU/LC changes.

Terminology

Infiltration refers to water movement from the surface into the subsurface. Terms such as *net infiltration, drainage*, or *percolation* are used to describe water movement below the root zone, and these can be equated to groundwater recharge as long as climate and LU/LC remain the same while water moves to the water table. *Recharge* can be defined generally as addition of water to an aquifer or, more strictly, addition of water from the overlying unsaturated zone or surface water body. *Diffuse (direct) recharge* refers to areally distributed recharge, such as from precipitation or irrigation over large areas, whereas *focussed, indirect, or localized recharge* refers to concentrated recharge from surface topographic depressions, such as streams, lakes, and playas. *Mountain-front* and *mountain-block recharge* have been defined as water entering adjacent inter-mountain basin-fill aquifers, with its source in the mountain front or mountain block (Wilson and Guan, 2004). Previous studies distinguish *direct mountain-front recharge* from *indirect mountain-front recharge* to include transfer of subsurface water from the adjacent mountain block (Wilson and Guan, 2004). *Piston flow* refers to uniform downward movement of water through the unsaturated zone that displaces existing water without bypassing it and should be distinguished from *preferential flow* or non-uniform downward water movement along preferred pathways, such as fractures and roots.

The definition of climate regimes used in this study was developed by United Nations Educational, Scientific, and Cultural Organization (UNESCO, 1979) on the basis of the ratio of mean annual precipitation to potential evapotranspiration (PET): hyperarid ($<0{\cdot}05$), arid ($0{\cdot}05$–$0{\cdot}2$), semiarid ($0{\cdot}2$–$0{\cdot}5$), dry subhumid ($0{\cdot}5$–$0{\cdot}65$), and humid ($>0 \cdot 65$) (Figure 1). Extensive (semi-) arid regions are found in the western US and Canada, southern and eastern areas of S. America, northern and southern areas of Africa, the Middle East, central Asia, and most of Australia. LU varies from natural to cultivated ecosystems. Cultivated areas include dryland (non-irrigated, rain-fed) and irrigated systems.

RECHARGE RATES IN (SEMI-) ARID REGIONS

The compilation of recharge rates for each of the major continents allows us to evaluate the range of recharge rates in various settings (Appendices I, II; Table I; Figures 1–4). Different approaches for regionalizing point recharge estimates are reviewed because regional estimates are most important for water resources. The relative importance of piston and preferential flow is evaluated by comparing recharge rates on the basis of different techniques. Appendices I and II and Table I include additional recharge rates beyond those discussed in the following sections on recharge in different regions. The recharge data are synthesized to assess impacts of climate variability and LU/LC changes on recharge.

Africa

Intensive recharge studies have been conducted in different countries in Africa (Appendices I, II; Table I; Figure 2). Data from the Sahara/Sahel tend to exhibit piston-flow behaviour and record variations in recharge rates at decadal to century scales in response to climate variability and LU change. In contrast, land surfaces are much older in southern Africa, and preferential flow is apparent particularly in Botswana and South Africa.

Regional recharge estimates in N. Senegal based on groundwater chloride data from 119 dug wells ranged from 1 to 20 mm year^{-1} (Appendices I, II) (Edmunds and Gaye, 1994). These recharge rates are consistent with estimates based on unsaturated zone chloride from 15 separate sites and tritium from 2 sites, which suggest predominantly piston-type flow (Appendices I, II; Table I; Edmunds and Gaye, 1994; Gaye and Edmunds, 1996). Recharge rates are highest ($\sim$20 mm) where Quaternary sands are thickest and decrease to lower values ($\sim$1 mm year^{-1}) where finer textured soils occur.

Recharge studies of the Continental Terminal aquifer (Eocene–Pliocene; silty sandstone) in south-west Niger indicate that cultivation increases recharge by about an order of magnitude. Natural ecosystems consist of patterned woodland termed *tiger bush* over the lateritic plateaus (banded pattern of alternating rows of

DOI: 10.1002/hyp

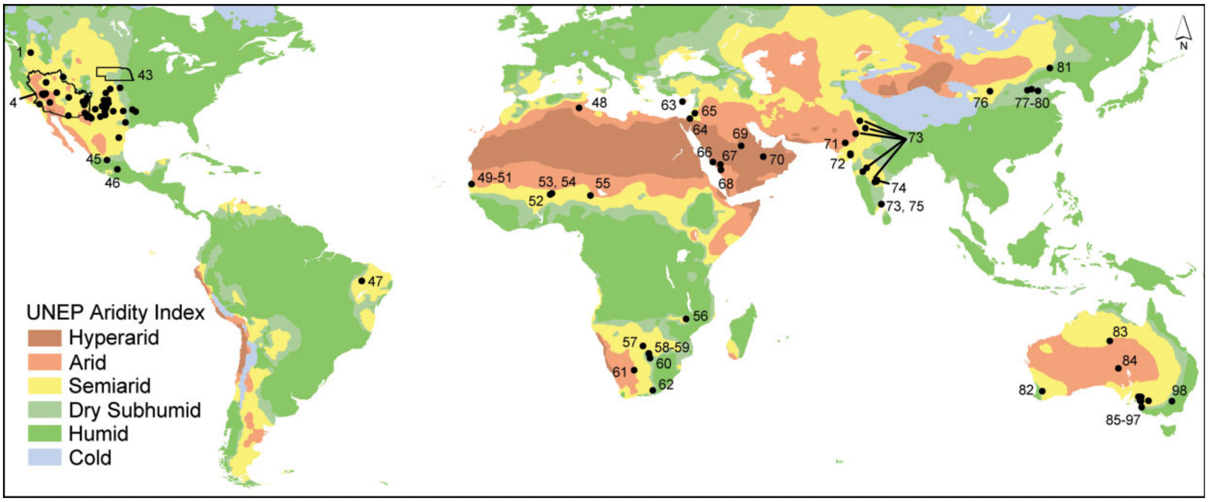

Figure 1. Global distribution of climatic zones (UNESCO, 1979). Information on recharge studies is in Appendix I. Location ID's for the SW US were omitted owing to the high density of study locations; refer to Figure 4. Detailed site locations and land use/land cover for Africa and Australia are available in Figures 2 and 3

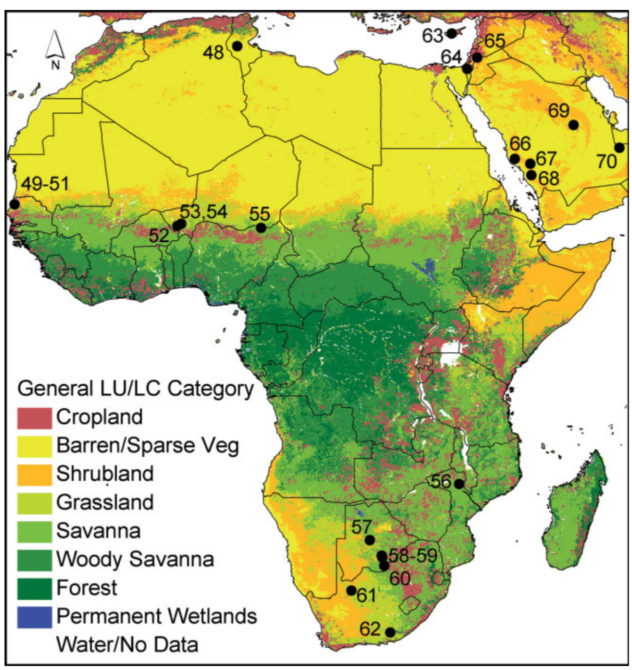

Figure 2. Distribution of recharge studies in Africa on a base map of land use/land cover settings (Diechmann and Eklundh, 1991). Information on recharge studies is in Appendix I

bare soil and bush) and open savanna (trees, shrubs, and grass) over slopes and in valley bottoms. A mean recharge rate of 13 mm year^{-1} was estimated using the chloride mass balance (CMB) approach at one location beneath tiger bush over a 70-m-deep profile that represents an average of over 790 years (Bromley *et al.*, 1997). Recharge rates in areas of natural savanna ecosystems range from 1 to 5 mm year^{-1} and were estimated

DOI: 10.1002/hyp

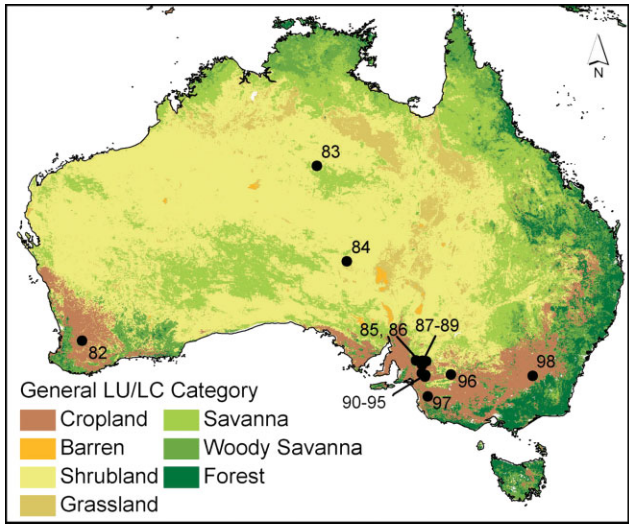

Figure 3. Distribution of recharge studies in Australia on a base map of land use/land cover settings (Diechmann and Eklundh, 1991). Information on recharge studies is in Appendix I

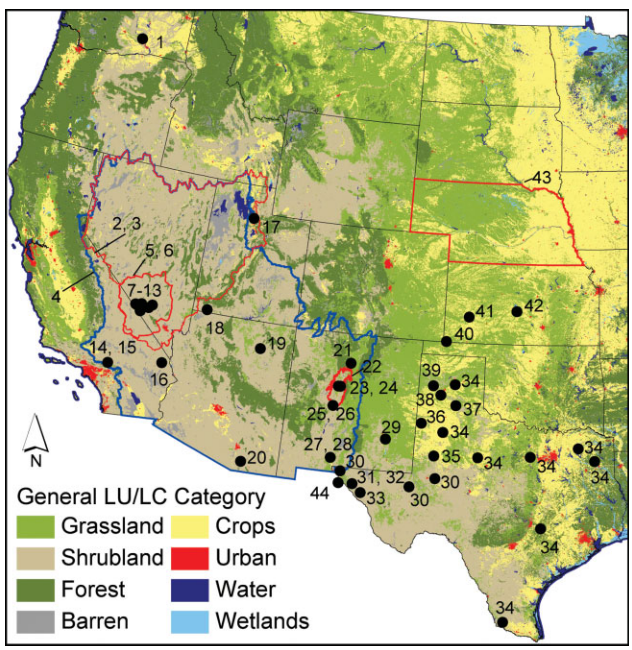

Figure 4. Distribution of recharge studies in the United States on a land use/land cover map based on Vogelmann *et al*. (2001). Information on recharge studies is in Appendix I

using an analytical model that takes into account the water-table rise to interpret groundwater ^{3}H and ^{14}C data (Favreau *et al*., 2002b). Replacement of natural savanna by millet fields and fallow periods leads to soil crusting, increased runoff, and focussed recharge in endoreic ponds (Leduc *et al*., 2001). Long-term groundwater level rises (0·1–0·47 m year^{-1}; 1963–1999) in cleared areas result from increased recharge rates of 10 to 47 mm year^{-1} (median 10 mm year^{-1}; porosity = 0·10) (Leduc *et al*., 2001). Larger groundwater

DOI: 10.1002/hyp

Table I. Detailed estimates of recharge based on 'depth-to-peak' tritium method

Ref.	Country/region	# Sites	P mm year^{-1}	^{3}H peak m	Value TU	Vel mm year^{-1}	R mm year^{-1}	Additional information
SW North America								
18	UT	7	210	3·5–>28·7	1·5–17·2	97–755	2·6–>57	Sandstone and sandy soil
32	Hueco Bolson, TX	1	280	1·4	23–29	56	<7	Ephemeral stream, clay to muddy-sandy-gravel
38	N. SHP	1	485	6·6	156	220	77	Playa
39	SHP	1	500	14·4	—	490	120	Playa, clay underlain by sand
Africa								
49	Senegal	2	290	12, 20	—	—	22, 26	Sand, dryland ag.
61	S. Africa	2	336	22	—	611	13	Sand, savanna
China								
77	Shanxi Province	2	550	5·6, 10·5	318, 235	255, 300	48, 68	Loess
81	Inner Mongolia	2	360	6·4, 10·4	558, 230	265, 304	40, 47	Loess
Australia								
91	S. Australia	3	340	1·5, 2·9, 5·3	3·0, 5·2, 5·6	—	8, 13, 17	Cleared, crops/pasture

Ref., reference number referring to references in Appendix I; P, precipitation; ^{3}H peak, depth of tritium peak; Value, amount of tritium measured in sample; Vel, velocity of tritium (peak/(year sampled-1963)); R, recharge determined using tritium method.

level rises from 1992 to 1999 (median 0·2 m year^{-1}) resulted from increased average recharge rates of 20 mm year^{-1} (Appendix I). These groundwater level rises occurred despite severe droughts during the 1970s and 1980s. Increased recharge related to land clearing can be extended to the Iullemmeden basin (Leduc *et al*., 2001). Therefore, LU/LC changes exert a significant influence on groundwater recharge in these regions.

The importance of preferential flow in controlling recharge is shown by many studies in Botswana and S. Africa. Large-scale recharge studies were conducted in central and eastern Botswana in cooperative programmes between the Botswana and Dutch governments (Selaolo *et al*., 1996; de Vries *et al*., 2000). Recharge rates in the central Kalahari are extremely low (~1 mm year^{-1}) where precipitation is low (350–400 mm year^{-1}) (de Vries *et al*., 2000). Differences in recharge rates based on chloride data in the unsaturated zone (average 3 mm year^{-1}; range 1–10 mm year^{-1}) and saturated zone (average 7 mm year^{-1}) in the eastern Kalahari Desert were attributed to focussed flow and preferential flow (Appendices I, II; de Vries *et al*., 2000). This region is characterized by thick sandy soils with calcrete and silcrete. Evidence of focussed flow is provided by low chloride concentrations beneath surface pans (e.g. 10 mg l^{-1} beneath Legape Pan), which result in local recharge rates of 50 mm year^{-1} (de Vries *et al*., 2000). Preferential flow is indicated by deep penetration of bomb-pulse tritium (4–5 TU to a depth of 42 m) (Figure 5) (Selaolo, 1998; de Vries *et al*., 2000). Evidence of preferential flow in the southern Kalahari (S. Africa) is indicated by higher recharge rates based on tritium distribution (13 mm year^{-1}, Appendix I, Table I) relative to those based on chloride in the unsaturated zone (1·8 and 5 mm year^{-1}; Appendices I, II; Table 1) (Butler and Verhagen, 2001). The importance of preferential flow should be considered in developing regional recharge estimates for water resource assessment.

Australia

Much of the recharge work in Australia focussed on dryland salinity issues (Figure 3). The salinity problem is extreme in the Murray River Basin, which drains a 300 000-km^2 area and is a major water source for irrigation and urban areas. Rising salinity in the Murray River has been attributed partly to increased recharge associated with replacement of deep-rooted eucalyptus mallee vegetation with shallow-rooted crops and pasture

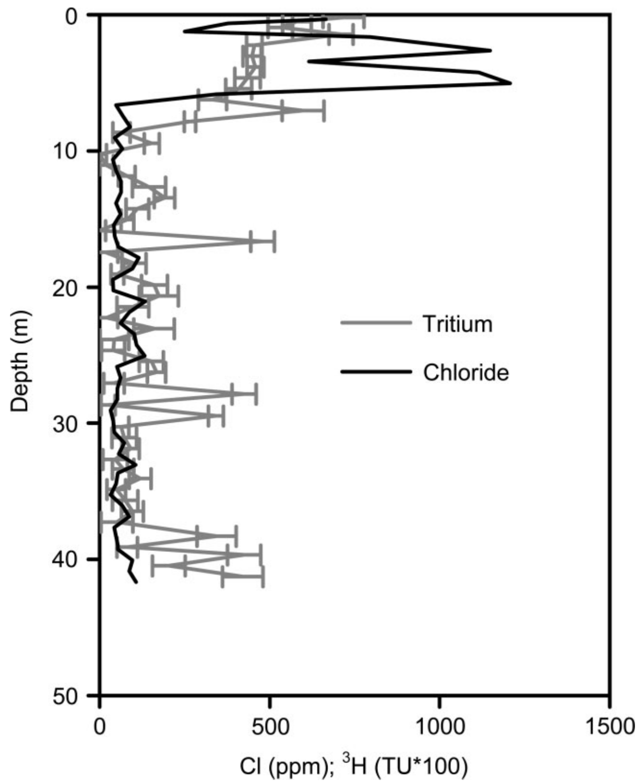

Figure 5. Chloride and tritium profiles in a selected borehole in eastern Botswana, borehole LB3B (modified from Selaolo, 1998)

in the late 1800s and early 1900s. Higher recharge flushes salts that accumulated in the unsaturated zone over thousands of years and increases hydraulic gradients to streams (Herczeg *et al*., 2001). Cook *et al*. (2001) estimated an increase in salinity of 0·1 to 3·4 tons day^{-1} km^{-1} of the Murray River (or a 75% increase) by year 2100 as a result of dryland agriculture. Several studies have estimated low recharge rates ($\sim$0·1–1 mm year^{-1}) beneath native mallee vegetation using the CMB approach (Appendices I, II; Allison *et al*., 1985; Leaney and Allison, 1986; Barnett, 1989; Cook *et al*., 1989; Allison *et al*., 1990; Salama *et al*., 1993; Cook *et al*., 1994). The time required to accumulate chloride in these profiles ranges from 4000 to 40 000 years (Allison *et al*., 1985). In contrast, recharge beneath areas that have been cleared of mallee increased up to about 2 orders of magnitude to between $\sim$1 and 50 mm year^{-1} (Appendices I, II; Figure 6; Allison and Hughes, 1983; Allison *et al*., 1985, 1990; Barnett, 1989; Cook *et al*., 1989, 1992b, 2004; Walker *et al*., 1991; Cook and Kilty, 1992; Salama *et al*., 1993; Leaney and Herczeg, 1995). Recharge rates in cleared areas were generally estimated using displacement of the chloride peak with depth (Cook *et al*., 1989; Walker *et al*., 1991) (Figure 7); however, the penetration depth of bomb tritium and bomb chlorine-36 was also used in a limited number of sites, which resulted in recharge rates from 8 to 17 mm year^{-1} (Cook *et al*., 1994). Spatial variability in recharge in areas of cleared vegetation has been attributed primarily to variations in soil texture and secondarily to differences in precipitation (Allison *et al*., 1990). Mean recharge rates at different sites range from $<$1 to 9 mm year^{-1} (Maggea) at a clay-rich site to 1 to $>$50 mm year^{-1} (Borrika) and $<$5 to $>$51 mm year^{-1} (Kulkami) at sandy sites (Appendix I). In addition, recharge rates in a sand dune area near Borrika correlated with variations in clay content in the upper 2 m of the soil profile (Cook *et al*., 1992b).

Developing estimates of regional recharge rates in various parts of Australia is complicated because many recharge estimates are based on point data from unsaturated zone chloride profiles. Regional recharge rates

DOI: 10.1002/hyp

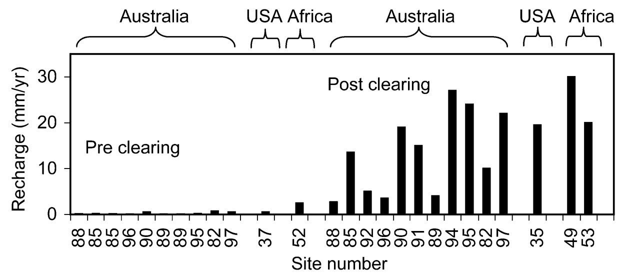

Figure 6. Average recharge rates before and after clearing of native vegetation in S. Australia, SW US, and Africa (Senegal and Niger). Refer to site numbers for references listed in Appendix I

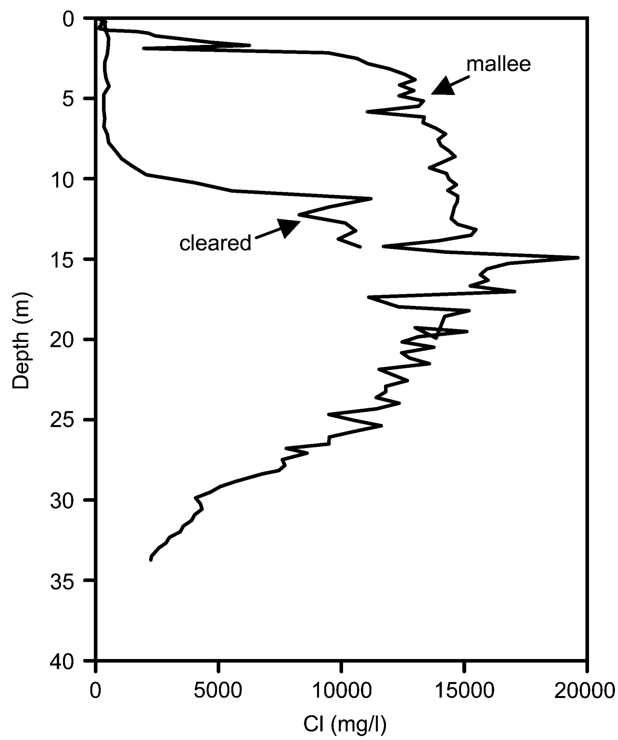

Figure 7. Comparison of chloride profiles in a vegetated and cleared area, boreholes BVD02 and BUF05 (modified from Cook *et al*., 1989)

were estimated for a ~72 000-km^2 area within the Murray River Basin using representative unsaturated zone profiles for seven different land units, with much of the area represented by sand dunes (~40%) and calcrete plains (~30%) (Allison *et al*., 1990). Electromagnetic (EM) induction was used to extrapolate and interpolate between point recharge estimates at a 14-ha field site (Borrika) using ground-based EM induction surveys (Cook *et al*., 1989, 1992a) and over a 32-km^2 area using airborne EM surveys (Cook and Kilty, 1992) (Appendix I). High correlations between recharge and apparent electrical conductivity measured by EM devices were attributed to differences in recharge being controlled primarily by variations in clay content (Cook *et al*., 1992a). Leaney and Herczeg (1995) estimated regional recharge rates for a 3000-km^2 area using groundwater hydraulic, chemical, and isotopic data and evaluated spatial variability in recharge using unsaturated zone data for different LUs (native vs cleared; irrigated vs non-irrigated) and soil textures (sand vs clay) (Appendix I).

DOI: 10.1002/hyp

Preferential and focussed flows are also important in Australia. Direct evidence of preferential flow is provided by unsaturated zone chloride profiles in sinkholes (secondary, small, deep depressions within primary sinkholes), which result in recharge rates of >60 mm year^{-1} relative to 0·1 mm year^{-1} for primary sinkholes (large, shallow depressions) and 0·1 mm year^{-1} for calcrete flats (Appendices I, II) (Allison *et al.*, 1985). However, groundwater studies indicate that point sources such as sinkholes contribute <10% of total recharge (Herczeg *et al.*, 1997). Studies in the Ti-Tree Basin in central Australia indicate that flood flows from ephemeral streams result in a recharge rate of 1·9 mm year^{-1}, which is much higher than recharge throughout the remainder of the basin (∼0·2 mm year^{-1}) (Appendices I, II) (Harrington *et al.*, 2002).

China

Information on recharge in China is limited (Figure 1). Detailed recharge studies have been conducted in loess deposits at sites in Inner Mongolia and Shangxi provinces on the basis of unsaturated zone tritium and chloride profiles (Figure 1; Appendices I, II; Table I) (Ruifen and Keqin, 2001). Loess consists of predominantly silt-sized particles and is generally enriched in carbonates. Loess is characteristic of widespread regions in China (440 000 km^2), particularly along middle reaches of the Yellow River, where it is up to 100- to 200-m thick. Four tritium profiles were measured to a maximum depth of 21 m (Figure 8; Appendix I; Table I). Peak tritium concentrations were up to 550 TU. Recharge rates of 40 to 68 mm year^{-1} (9–12% of long-term average annual precipitation) were calculated from average water content in profiles above tritium peak depths (range 5·6–10·5 m) (Appendix I; Table I). Although recharge rates based on unsaturated zone chloride data were quite variable (85–288 mm year^{-1}), variability may be related to uncertainty in chloride concentrations in precipitation, which were based on limited data (monthly records of 5–7 months) (Appendices I, II). The high recharge rate of 288 mm year^{-1} is related to a precipitation chloride value of 10·2 mg l^{-1}, which is much higher than the value used at the other site (2·2 mg l^{-1}). If the latter value were used, the recharge rate would be reduced from 288 to 62 mm year^{-1}, similar to values estimated from tritium data.

The impact of vegetation on the water balance in the Tengger Desert in Central China was evaluated by Wang *et al.* (2004a, b). Re-vegetation in this region has been going on for 40 years to stabilize shifting sand dunes. Non-vegetated and vegetated weighing-lysimeter experiments indicate that vegetation used all available soil water, whereas soil water drained out of the base of the non-vegetated lysimeter, resulting in an average recharge rate of 48 mm year^{-1}, 25% of long-term precipitation (Wang *et al.*, 2004a).

Quantifying groundwater recharge is crucial for assessing sustainability of irrigated agriculture in the North China Plain (NCP, 320 000 km^2). NCP is China's most important center of agricultural production, accounting for 50% of the wheat and 33% of the maize production in China (Kendy *et al.*, 2003). The monsoon climate results in most precipitation occurring from June to September. Although water requirements for summer maize and winter wheat are comparable, irrigation requirements are much greater for winter wheat because it is grown during the dry season. Approximately 70% of the land is cultivated with groundwater-irrigated winter wheat (Foster *et al.*, 2004). Although recharge has increased as a result of irrigation, increased pumping has offset the higher recharge rates, which resulted in water-table declines of 20–30 m over the past 30 years and large reductions in stream flow (Foster *et al.*, 2004; Liu and Xia, 2004). Similar overdevelopment of groundwater for agricultural production is going on in the east Hebei Plain of North China (Jin *et al.*, 1999). In the Heilonggang region, agriculture accounts for 84% of water use. Excessive groundwater withdrawals have resulted in groundwater level declines of 2–3 m year^{-1} (Liu and Xia, 2004). Water balance modelling for a 3-year period calibrated using soil moisture data at 16 sites results in a range of recharge rates from 36 to 209 mm year^{-1}, representing 8–25% of precipitation plus irrigation (Appendix I; Kendy *et al.*, 2003). The recharge rates represent a wide range of irrigation applications; a 209-mm year^{-1} recharge is the most realistic, according to water applied to farms during the 3-year study period. Over a 50-year period, simulated recharge ranged from 50 to 1090 mm year^{-1} in the same region, representing more varied climate and irrigation applications (Appendix I; Kendy *et al.*, 2004).

DOI: 10.1002/hyp

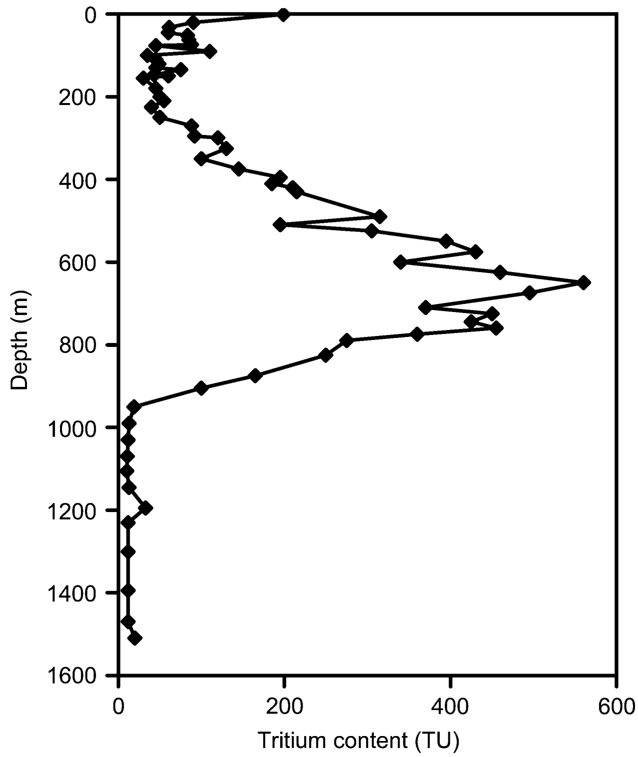

Figure 8. Representative tritium profile at a site in China, borehole CHN/88 (modified from Ruifen and Keqin, 2001)

Studies by Jin *et al.* (1999) suggest ways of harmonizing crop production with water availability to minimize groundwater pumpage. Because summer maize production coincides with peak rainfall related to summer monsoons in the region, it requires little or no irrigation. Winter wheat has the greatest irrigation requirements because winter precipitation is low. Optimizing crop production (e.g. less winter wheat) relative to precipitation and soil water availability should improve sustainability of agricultural production and reduce impacts on groundwater. Recharge estimates based on tritium injection ranged from 92 to 243 mm year^{-1} in mostly irrigated regions that varied with crop type, cultivation practices, irrigation amounts, and soil types (Appendix I; Jin *et al.*, 2000). Information on recharge is critical for developing sustainable groundwater management plans in these regions.

India

Natural recharge has been estimated for the four main hydrogeologic provinces in India: (1) alluvium (Indo-Gangetic plain in north India; Quaternary age), (2) basalt (Deccan trap in west and central India; Cretaceous age), (3) granites and gneisses (southern and south-eastern India; Archaean age), and (4) semi-consolidated sandstones all over the country (Proterozoic, Paleozoic, and Mesozoic ages) (Rangarajan and Athavale, 2000). Recharge was estimated using tritium injection. Tritium was generally injected at depths of 0·6 to 0·8 m before the monsoon period (June–Sept), and soil profiles were sampled to depths of 2 to 6 m (0·1-m increments) at the end of the monsoon period, with the exception of dune soil in desert areas, which was sampled at the end of the year to account for post-monsoon ET (Athavale *et al.*, 1998). Recharge studies were usually conducted in grassy dryland (rain-fed) areas. Tritium was generally injected at 25 to 30 locations at each site, and an arithmetic average recharge rate was calculated for each site. Average recharge rates at all sites ranged from 24 to 198 mm year^{-1}, representing 4–20% of local average seasonal precipitation (Rangarajan

DOI: 10.1002/hyp

and Athavale, 2000). Average recharge rates at nine (semi-) arid sites ranged from 46 to 161 mm year^{-1}, representing 9–20% of local average seasonal precipitation (Appendix I). Local variability in recharge at each site was high (coefficient of variation 40–90%) and was attributed to soil heterogeneity. Recharge correlated with seasonal precipitation for each of the four hydrogeologic provinces ($r^2 = 0{\cdot}69–0{\cdot}92$, 35 sites). Results from the tritium injection method compared favourably with the water-table fluctuation method (Athavale *et al*., 1983; Rangarajan and Athavale, 2000).

The tritium injection approach quantifies piston-flow recharge; however, preferential flow may be significant, particularly in fractured rocks. To assess the importance of preferential flow, different tracer approaches (tritium mass balance and peak penetration and groundwater CMB) were used in three representative settings (alluvium, fractured granite, and semi-consolidated sandstones; Sukhija *et al*., 2003). Recharge estimates based on peak tritium and total tritium mass balance in the alluvium were similar, indicating predominantly piston flow. In contrast, recharge estimates based on saturated zone chloride were four times greater than those based on unsaturated zone chloride profiles in the granites and gneisses, indicating significant preferential flow (Appendix I). Similar results were obtained in semi-consolidated sandstones, indicating 33% preferential flow. These studies evaluated natural recharge in India but did not estimate recharge from surface water bodies or irrigation return flow.

United States

Intensive recharge studies have been conducted in (semi-) arid regions of the SW US, primarily to characterize sites for low-level and high-level radioactive waste disposal (Prudic, 1994; Scanlon, 1996; Flint *et al*., 2001) but also to evaluate water resources (Izbicki, 2002; Sanford *et al*., 2004) (Appendices I, II; Table I; Figure 4). Much of the SW US is within the Basin and Range physiographic province, which consists of linear mountain blocks trending north-northwest separated by broad, fault-bounded basins filled with alluvial sediments. The aridity index ranges from hyperarid (in Death Valley, California) to humid (north-central Nevada) (Flint *et al*., 2004).

Detailed field studies were conducted at Yucca Mountain, Nevada (60 km^2 area), the proposed site for high-level radioactive waste disposal in the US (Flint *et al*., 2002). The unsaturated zone consists of a 550- to 750-m-thick section of volcanic tuffs. Water content monitoring in 69 boreholes over 11 years has resulted in an average recharge rate of 11·6 mm year^{-1}, 20 to 30 mm year^{-1} in upland areas and 10 to 20 mm year^{-1} in lowland areas (Flint *et al*., 2002). The volume of water recharged in different settings was: ridge top, 1 109 170 m^3 (19% of area); side slope, 4 310 280 m^3 (73% of area); terrace, 422 090 m^3 (7%); and channel 65 006 m^3 (1%) (Flint and Flint, 2000). Channels, despite the large volumes of water available from concentrated runoff, contribute much less water for recharge than all the other settings. Recharge rates based on the unsaturated zone chloride data ranged from 0·01 to 10 mm year^{-1}, whereas rates based on the chloride in a perched aquifer ranged from 8 to 15 mm year^{-1} (Appendices I, II; Flint *et al*., 2002). Higher recharge rates for the perched aquifer are attributed to increased recharge during the Pleistocene pluvial period relative to the Holocene semiarid period. Penetration of bomb-pulse chlorine-36 to depths of 300 m is attributed to preferential flow, related to thin soils (<3 m), fracture flow as a result of high infiltration rates (1–10 mm year^{-1}), and continuous fracture pathways (Flint *et al*., 2002).

The detailed field studies at Yucca Mountain formed the basis for development of a general conceptual model (Flint *et al*., 2001) and numerical model (INFIL) based on water and energy balance processes that assume that all processes controlling net infiltration (equated to recharge) occur within the top 6 m of surficial materials. INFIL is based on daily climate parameters (precipitation, air temperature, PET) and includes five to seven soil layers and surface water routing. Modelled recharge rates range from ~0 to 80 mm year^{-1} (average ~5–10 mm year^{-1} across the repository block area, 3–6% of average precipitation (170 mm year^{-1}), (Appendix I)) for the Yucca Mountain region. INFIL was also applied to Death Valley (45 288 km^2) and resulted in an average recharge rate for 1950 to 1999 of 2·8 mm year^{-1}, corresponding to average precipitation of 170 mm year^{-1} (Nevada and California) (Appendix I; Hevesi *et al*., 2003).

DOI: 10.1002/hyp

However, recharge is highly variable spatially, ranging from 0 to >500 mm year^{-1}. Highest recharge rates (>500 mm year^{-1}) were estimated for active channel locations in mountain-block settings (Spring Mountains), where precipitation is highest (~550 mm year^{-1}), soils are thin, and bedrock permeability is high (Paleozoic carbonates). In contrast, simulated recharge rates in granites at the summit of Paramint Range are much lower (<2 mm year^{-1}) because of low permeability, even though precipitation exceeds 400 mm year^{-1}.

The model area was expanded from Death Valley to the entire Great Basin (374 218 km^2) and to the (semi-) arid SW US (km^2), as defined by Stonestrom and Leake (in press) using a newly developed, simpler, Geographic Information Systems (GIS)-based Basin Characterization Model (BCM) (Flint *et al.*, 2004; Flint and Flint, in press) (Figure 9). BCM differs from INFIL in that monthly climate data are used, only one soil layer is used, and there is no surface water routing. The lack of surface water routing results in BCM simulating total potential recharge, which is a combination of in-place recharge and runoff, and assumes that all runoff becomes recharge. Results from the two models compared favourably for Death Valley (INFIL: 2·8 mm year^{-1}; BCM, 1·7 mm year^{-1}). Total potential recharge in the Great Basin averaged 16·9 mm year^{-1} (range: 0–>1300 mm year^{-1}) for 1950 to 1999 and compared well with CMB estimates within the basin (Flint *et al.*, 2004). Field calibration of BCM in the Great Basin indicates that 10% of runoff recharges in the north and 90% in the south, resulting in an average recharge rate of 9·7 mm year^{-1} (Appendix I; Flint *et al.*, 2004). Simulated total potential recharge for the (semi-) arid SW US averaged 11·2 mm year^{-1} (0–1612 mm year^{-1}), corresponding to average annual precipitation of 301 mm year^{-1} (51–1931 mm year^{-1}) for 1971 to 2000. High recharge rates were estimated beneath ephemeral stream settings in regions of the SW US: 1·3 m year^{-1}, Oro Grande Wash, California (Izbicki, 2002), and 41–91 mm year^{-1}, 12–15% of streamflow, Amargosa Arroyo, Nevada (Stonestrom *et al.*, 2004) (Appendix I).

Regional recharge studies were also conducted in the Middle Rio Grande Basin (MRGB) in Central New Mexico. An average recharge rate of 8·5 mm year^{-1} (3% of precipitation) was estimated for the MRGB (7900 km^2 area) using a steady state, inverse groundwater model based on 200 hydraulic head and 200 ^{14}C measurements (Appendix I; Sanford *et al.*, 2004). The ^{14}C age estimates are robust because corrections were minimal in this siliciclastic system. Recharge occurs primarily in surrounding mountain-block and mountain-front settings through ephemeral streams, with little or no recharge in inter-stream basin-floor settings. Model recharge estimates for the eastern mountain-front region (Sandia Mountains and Abo Arroyo) correspond to independent estimates from the CMB approach (average 8·7 mm year^{-1}, 2% of precipitation) (Anderholm, 2001). Stream recharge rates up to 720 m year^{-1} were calculated using temperature monitoring (Appendix I; Constantz and Thomas, 1996; Constantz *et al.*, 2002).

Regional recharge was estimated for the state of Texas (~700 000 km^2) on the basis of 1-D unsaturated zone modelling for a 30-year period at 13 sites (1152–14 980 km^2 area) representing various climate, vegetation, and soil types (Appendix I; Keese *et al.*, 2005). GIS software was used to spatially weight recharge estimates for different vegetation and soil types at each site. The relationship between simulated average recharge rates for each site and long-term (30-year) average precipitation ($r^2 = 0{\cdot}81$) allowed regionalization of site-specific recharge estimates to the entire state. A regional recharge rate of 11 mm year^{-1} (2% of precipitation) was estimated for the southern High Plains in Texas using groundwater chloride data (Appendices I, II; Wood and Sanford, 1995). Unsaturated zone studies indicate that recharge is focussed beneath ephemeral lakes or playas (60–120 mm year^{-1}) and that there is little or no recharge in interplaya settings (Wood and Sanford, 1995; Scanlon and Goldsmith, 1997).

Recharge studies in Utah provide examples of various approaches that can be used to estimate recharge. Kilometer-length trenches (1 m wide, ≤7 m deep) excavated into the Navajo sandstone in Sand Hollow (50 km^2 upland basin; south-west Utah) showed higher diffuse recharge in areas of exposed sandstone bedrock and of coarse-grained soil, and much lower recharge in areas of fine-grained soil (Heilweil and Solomon, 2004). Low chloride concentrations in the vicinity of fractures indicate preferential flow. Recharge rates range from 2 to 57 mm year^{-1} according to unsaturated zone tritium data, and from 0·5 to 13 mm year^{-1} according to unsaturated zone chloride data beneath the bulge. Recharge rates based on saturated zone

DOI: 10.1002/hyp

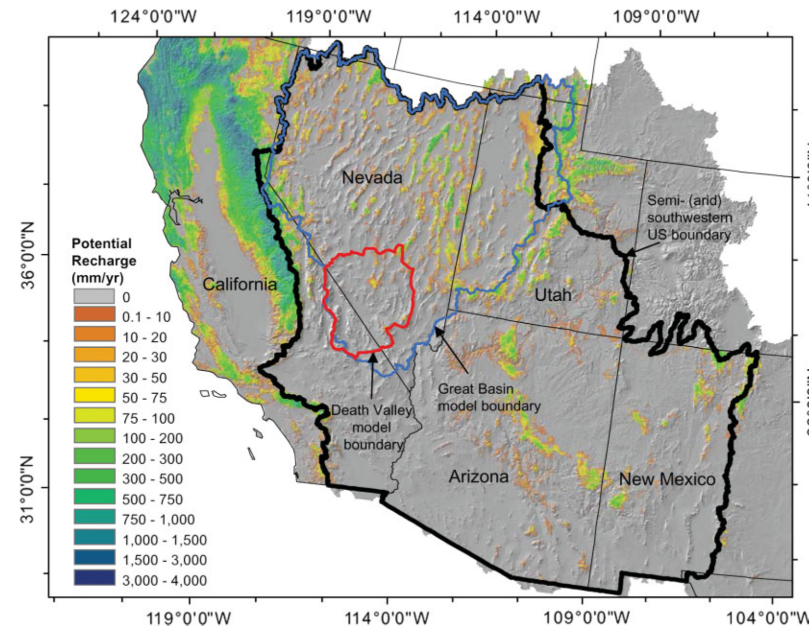

Figure 9. Map of average annual potential recharge (30-year) using BCM for (semi-) arid SW US, shown within the thick black boundary line (Flint and Flint, in press)

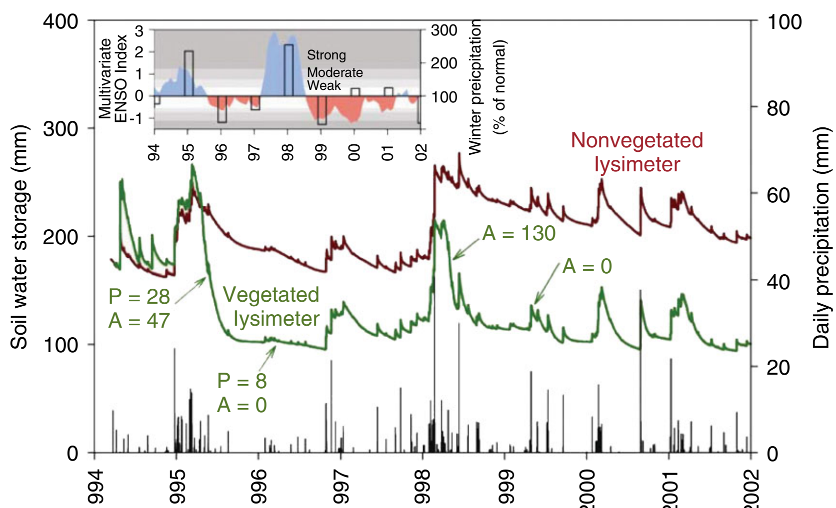

Figure 10. Measured soil water storage to a depth of 2 m in vegetated and non-vegetated lysimeters and daily precipitation depths at a site in the SW US. Inset indicates relationship between the Multivariate ENSO Index (blue shading: El Niño, red shading: La Niña) and percent of normal 1971 to 2000 winter precipitation (normal = 46 mm, Dec–Feb) (columns) at this site (from Scanlon *et al.*, 2005a)

chloride concentrations are similar (mean ~11 mm year^{-1}, ~5% of precipitation, range 3–60 mm year^{-1}) (Appendices I, II; Table I; Heilweil *et al.*, 2006). Noble gases and tritium–helium dating in the saturated zone were used to estimate recharge in eastern Salt Lake Valley in northern Utah (Manning and Solomon, 2004). Noble gases provide information on recharge temperature. Two-component mixing with mean mountain-block temperature (2 °C) and valley-floor temperature (13 °C) indicates that mountain-block recharge from the

DOI: 10.1002/hyp

adjacent Wasatch Mountains represents ≥30% and more likely 50 to 100% of recharge throughout the basin. Increasing ages away from the mountain front result in an age gradient of 5 years km^{-1}. This age gradient generally corresponds to an average volumetric recharge rate of 176 000 m^3 day^{-1} (porosity = 0·20) and a recharge rate of ~210 mm $year^{-1}$, which is based on a recharge area of 300 km^2 for the Wasatch Mountains (Appendix I). Knowledge of total recharge from tritium–helium dating and the fraction that is mountain-block recharge allowed estimation of mountain-block recharge rates.

Recharge studies were conducted in cold deserts in south-eastern Washington State in the rain shadow of the Cascade Mountains. The Hanford site (765 km^2 area) was established in 1943 by the US Department of Energy for production of nuclear materials; however, the mission changed to waste management in the 1980s, and the concern is that natural recharge could transport wastes to underlying aquifers. An average regional recharge rate of 11 mm $year^{-1}$ was estimated using GIS and point recharge estimates for various soil texture/vegetation combinations (Appendix I; Fayer *et al*., 1996). Point recharge estimates were based on weighing and non-weighing lysimeter data, water content monitoring, and environmental tracers (chloride and ^{36}Cl). Recharge rates ranged from 55·4 mm $year^{-1}$ (lysimeters, 8-year data) for non-vegetated, medium to coarse sand equivalent to a dune environment; 86·7 and 300 mm $year^{-1}$ (lysimeters) for non-vegetated, gravel over sand; 25·4 mm $year^{-1}$ (water content monitoring) for cheat grass with sandy loam; ≤0·1 mm $year^{-1}$ (CMB) for shrubs with silt loam; ≤0·3 mm $year^{-1}$ (CMB) for shrubs in loamy sand; to 0·4 to 2·0 mm $year^{-1}$ (CMB) for cheat grass in loamy sand (Appendix I; Fayer *et al*., 1996; Prych, 1998).

IMPACT OF CLIMATE VARIABILITY ON RECHARGE

Information on the impact of climate variability on recharge at inter-annual to millennial timescales is available for many regions. El Niño Southern Oscillation (ENSO) is the primary determinant of inter-annual climate variability globally. El Niño results in increased precipitation in many regions, including SW US, SE S. America, N. Australia, India, and SE Africa. In contrast, precipitation is reduced in NW US, Gulf of Mexico, NE S. America, most of Australia, and E. Africa (Ropelewski and Halpert, 1987; McCabe and Dettinger, 1999). La Niña generally has the opposite effect on precipitation. At decadal timescales, the Pacific Decadal Oscillation (PDO) impacts precipitation in the Americas and Australia (Mantua and Hare, 2002). Variations in precipitation caused by ENSO and PDO generally result in variations in streamflow (Redmond and Koch, 1991; Simpson *et al*., 1993; Kahya and Dracup, 1994; Piechota *et al*., 1998; Cayan *et al*., 1999; Lins and Slack, 1999). Studies in mountain-front settings in Arizona (US) indicate that increased stream flow results in up to 3 times higher recharge during periods of frequent El Niños (1977–1998) relative to periods dominated by La Niñas (1941–1957) on the basis of water-table fluctuations and gravity data (Pool, 2005). Similar results were found in California (US) (Hanson *et al*., 2004) and in Argentina (S. America) (Venencio, 2002). Increased precipitation and streamflow related to ENSO may also increase recharge in many other areas.

Elevated ENSO precipitation could also increase recharge in inter-stream settings through diffuse recharge; however, studies in SW US indicate that increased precipitation results in enhanced biomass productivity, which uses up all excess water, resulting in no net increase in groundwater recharge (Figure 10) (Scanlon *et al*., 2005a). Strong correlations between normalized difference vegetation index (NDVI, an indicator of vegetation productivity based on satellite data) and inter-annual precipitation variability related to ENSO in deserts in Australia, South America, and Africa (Anyamba and Eastman, 1996; Myneni *et al*., 1996) indicate that the processes described in SW US may apply to deserts globally, but has not been documented.

Climate variability at decadal to century timescales is archived in chloride profiles in N. Senegal (Cook *et al*., 1992b; Edmunds and Tyler, 2002). Chloride profiles (e.g. Louga 2, 3, and 18 profiles) have high concentrations corresponding to drought periods (e.g. Sahel drought 1970–1986) and low concentrations corresponding to periods of high precipitation (1950–1970). Precipitation during the Sahel drought (223 mm $year^{-1}$) was

DOI: 10.1002/hyp

much lower than the long-term average (356 mm year^{-1}) (Cook *et al*., 1992b). Estimated recharge rates for a chloride profile (Louga 18) range from 30 mm year^{-1} during drought (1970–1986) to >65 mm year^{-1} (1950–early 1960s) and 150 mm year^{-1} (1986–1990) during non-drought periods (Cook *et al*., 1992b). Another chloride profile (Louga 10) in this region contained a longer record (475 years) and correlated with variations in reconstructed water levels in Lake Chad, according to sedimentological and palynological records (Cook *et al*., 1992b). High chloride concentrations correspond to low water levels in Lake Chad and vice versa.

The impact of paleoclimate variations has been documented in the United States and Africa. Bulge-shaped chloride profiles in inter-stream settings throughout the SW US are attributed to higher recharge at depth (low chloride concentrations generally corresponding to the Pleistocene period 10 000–15 000 years ago) and buildup of chloride since that time during the Holocene (Figure 11) (Scanlon, 1991; Phillips, 1994; Tyler *et al*., 1996). The change in chloride concentrations corresponds to a change from humid conditions with mesic vegetation during the Pleistocene to semiarid conditions with xeric vegetation during the Holocene. Current water potential monitoring and modelling analysis indicate that xeric vegetation has been active throughout the Holocene in maintaining dry conditions in the root zone, resulting in discharge through ET rather than recharge (Walvoord *et al*., 2002; Scanlon *et al*., 2003). Therefore, there has been no recharge since the Pleistocene in these settings.

Regional evaluation of recharge in N. Africa indicates that recharge occurred during the Pleistocene prior to the Last Glacial Maximum (LGM), about 20 000 years ago in many basins; no recharge occurred during the LGM (~20 000–10 000 years) (suggested by a gap in the ^{14}C record between 5 and 15 pmc (% modern carbon)); and recharge occurred during the Holocene, mostly beneath river channels. Late Pleistocene recharge (~20 000–30 000 years) is recorded in confined aquifers in the Sirte and Kufra Basins in Libya (Edmunds and Wright, 1979), the Complexe Terminal aquifer in central Algeria (Guendouz *et al*., 2003), and the Continental Intercalcaire aquifer in Niger (Andrews *et al*., 1994). Noble gas recharge temperatures of Pleistocene water were up to 7 °C lower than current temperatures. Recharge during the Holocene was concentrated beneath river channels, as shown by a fresh-water zone beneath a proposed Holocene river (10 km wide × 130 km long) within the Sirte and Kufra Basins, with ages ranging from 5000 to 7800 years (Edmunds and Wright, 1979). Recharge occurred from the Tibesti Mountains to the south along a now-inactive river (Wadi Behar Belama) (Pachur and Kropelin, 1987). Recharge was focussed beneath the Nile River in Sudan, according to

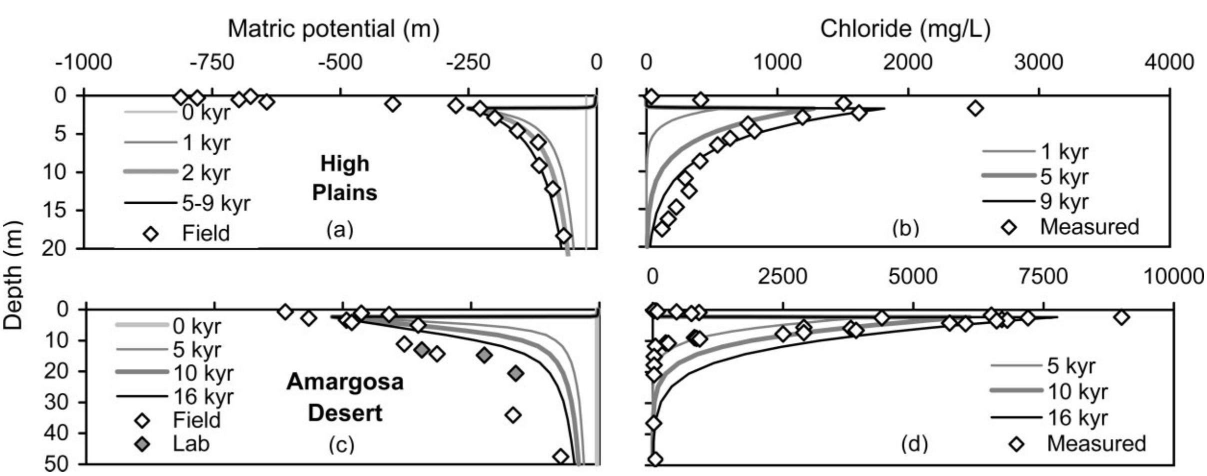

Figure 11. Simulated matric potential and chloride concentrations for selected sites in the SW US (from Scanlon *et al*., 2003). Time 0 kyr represents wet initial conditions (Pleistocene pluvial period). Remaining times represent periods of upward flow to a maximum time based on the CMB age at the base of the chloride bulge for each site. Measured matric potential and chloride profiles are shown for comparison with simulated profiles

DOI: 10.1002/hyp

isotopic and chemical compositions (Darling *et al.*, 1987). Focussed recharge beneath rivers generally ceased about 4000 to 5000 years BP, when the climate shifted to the current arid conditions.

IMPACT OF LAND USE/LAND COVER CHANGE ON RECHARGE

Most recharge studies have been conducted in natural settings. Estimated average recharge rates for 26 studies in large basins (40–374 000 km^2) with predominantly natural ecosystems range from 0·2 to 35 mm $year^{-1}$ (Figure 12). These recharge rates represent 0·1–5% of precipitation, and recharge increases with precipitation ($r^2 = 0{\cdot}46$). Previous studies have shown the importance of vegetation in controlling recharge in these natural ecosystems. Lysimeter studies in the Tengger Desert (China) and the Chihuahuan and Mojave Deserts (SW US) show recharge in non-vegetated areas up to 87 mm $year^{-1}$ and no recharge in vegetated areas (Gee *et al.*, 1994; Wang *et al.*, 2004a; Scanlon *et al.*, 2005b). Therefore, changing LU/LC from non-vegetated to vegetated conditions reduces recharge to zero.

Impacts of LU/LC changes on recharge are most obvious in Australia. Recharge rates in native mallee eucalyptus vegetation in Australia range from ~0·1 to 1 mm $year^{-1}$, whereas recharge in deforested areas is up to about 2 orders of magnitude higher (~1–50 mm $year^{-1}$) (Figure 6). Changes in recharge resulted from reduced interception, reduced ET, shallower rooting depths, and fallow periods. Groundwater tables in remnant eucalyptus vegetation are up to 2–7 m deeper than under adjacent cleared areas (McFarlane and George, 1992; Le Maitre *et al.*, 1999). Increased recharge related to deforestation in Australia has resulted in large increases in groundwater salinity. Field studies and numerical modelling have been used to examine different strategies, including reforestation and various agricultural management options, to control or reverse dryland salinity problems. Evaluation of 80 sites in western Australia indicated that reforestation of about 70–80% of a catchment would be required to achieve significant reductions in groundwater levels and salinity control (George *et al.*, 1999). Modelling analyses indicate that reforestation of 30 to 45% of catchments in a region in south-eastern Australia would be required to control salinity (Salama *et al.*, 1999; Zhang *et al.*, 1999). Agricultural options include reduction of fallow periods. Studies by O'Connell *et al.* (2003) indicate that long fallow periods potentially increase deep drainage by ~2 mm $year^{-1}$ relative to fully cropped systems over a wide rainfall range (134–438 mm $year^{-1}$). Similar studies have examined cropping intensification and various crop rotations to reduce recharge (Latta and O'Leary, 2003; Sadras and Roget, 2004).

There is considerable interest in afforestation for carbon sequestration as a result of the Kyoto protocol; however, potential impacts of these plantations on groundwater recharge should be considered. Studies have been conducted in Argentina in areas where pampas grasslands have been replaced by eucalyptus plantations

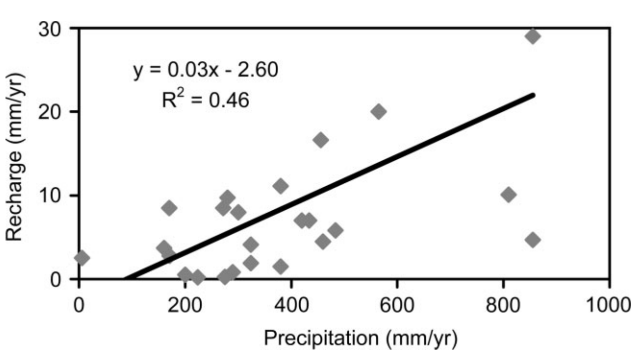

Figure 12. Relationship between recharge and precipitation from studies of large natural areas (40–374 200 km^2) using methods that reflect regional recharge rates (modelling, saturated zone CMB, micro-gravity, and water-table fluctuations) (Leaney and Allison, 1986; Edmunds *et al.*, 1988; Bazuhair and Wood, 1996; Sami and Hughes, 1996; de Vries *et al.*, 2000; Love *et al.*, 2000; Anderholm, 2001; Leduc *et al.*, 2001; Flint *et al.*, 2002, 2004; Favreau *et al.*, 2002b; Harrington *et al.*, 2002; Hevesi *et al.*, 2003; Goodrich *et al.*, 2004; Sanford *et al.*, 2004; Heilweil *et al.*, 2006; Keese *et al.*, 2005)

DOI: 10.1002/hyp

(Jobbagy and Jackson, 2004). Detailed studies of the impact of a 40-ha eucalyptus plantation on groundwater over 2 years indicated that groundwater discharged more than 50% of the days through ET depressing the water table by >0·5 m and increasing groundwater salinity by factors of 2–19, depending on soil texture (Jobbagy and Jackson, 2004; Engel *et al*., 2005). Studies in S. India suggest that eucalyptus plantations use twice as much water as millet crops, significantly reducing groundwater recharge (Calder *et al*., 1993).

Conversion of grassland and shrubland to crops also has significant impacts on recharge. Such conversions in the southern High Plains (US) changed systems from discharging through ET to recharging, with average recharge rates over large areas (up to 3400 km^2) of ~24 mm $year^{-1}$ (~5% of precipitation) (Scanlon *et al*., 2005b). Similar changes in recharge have been documented in the Great Plains, N. America (van der Kamp *et al*., 2003), and in Niger and South Africa (O'Connor, 1985; Le Maitre *et al*., 1999). In Niger, recharge rates increase from 1 to 5 mm $year^{-1}$ in savanna ecosystems to 10 to 47 mm $year^{-1}$ in cleared areas (Leduc *et al*., 2001; Favreau *et al*., 2002b). Impacts of LU/LC changes on recharge are much greater than those of climate variability in Niger because water level increases related to cultivation occurred during severe droughts in the 1970s and 1980s. Cultivation results in increased diffuse recharge in the southern High Plains, similar to cultivated areas in Australia, whereas cultivation results in increased runoff and focussed recharge beneath endoreic ponds in the Great Plains (US). Causes of variations in recharge related to cultivation in the southern High Plains may be related to the absence of vegetation during fallow periods, which is consistent with lysimeter studies in the SW US and in China. Increased runoff and reduced infiltrability related to cultivation in the Great Plains are attributed to destruction of preferred pathways in frozen soil (van der Kamp *et al*., 2003). There is controversy about the impact of cultivation on diffuse versus focussed recharge in Niger (Leduc *et al*., 2001; Bromley *et al*., 2002; Favreau *et al*., 2002a). Bromley *et al*. (2002) suggested that both diffuse and focussed recharge may contribute to increased recharge beneath cultivated fields on the basis of increases in soil moisture below the root zone of millet fields based on neutron probe logging. However, Favreau *et al*. (2002a) argued that (1) millet can dry out soil profiles to 3·4 m depth; (2) the time required for diffuse recharge to reach the water table (~35 m) is >100 years, whereas clearing took place only 50 years ago; and (3) the generally low total dissolved solids in groundwater is not consistent with flushing of salts that accumulated in the unsaturated zone. Increased runoff has been related to reduced organic matter and crusting in cultivated soils (Leduc *et al*., 2001).

Compilation of recharge rates from studies in irrigated areas in China, Australia, and the US indicates that recharge rates (10–485 mm $year^{-1}$) increase as a function of precipitation plus irrigation (average 15%, range 1–25%; $r^2 = 0{\cdot}64$; Figure 13), according to modelling studies in China and field tracer studies in the SW US and Australia (Leaney and Herczeg, 1995; Kendy *et al*., 2003; McMahon *et al*., 2003; Scanlon *et al*., 2005b; McMahon *et al*., 2006). If irrigation water is derived from surface water sources, such increases in recharge can result in shallower water tables and water logging of soils. In groundwater-fed irrigation systems, increased irrigation pumpage greatly outweighs increased recharge rates, resulting in large groundwater level declines

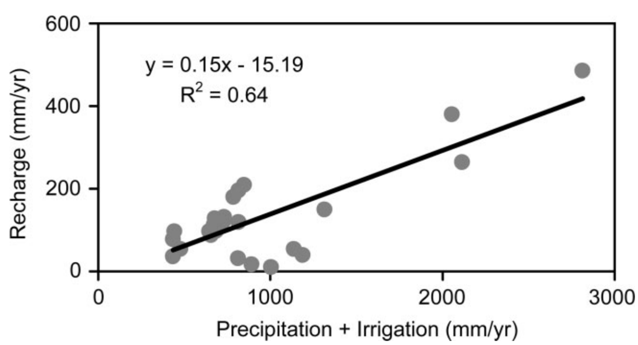

Figure 13. Relationship between recharge and applied water (precipitation and irrigation) in irrigated settings (Leaney and Herczeg, 1995; Kendy *et al*., 2003; McMahon *et al*., 2003; Scanlon *et al*., 2005b; McMahon *et al*., 2006)

DOI: 10.1002/hyp

(e.g. ∼20–30 m, China; ≤25 m, southern High Plains (US), 20–30 m, Spain) (Bromley *et al*., 2001; Foster *et al*., 2004; Liu and Xia, 2004; Scanlon *et al*., 2005b). Therefore, cultivation (irrigated and non-irrigated) has large impacts on groundwater recharge and water resources.

COMPARISON OF RECHARGE ESTIMATION TECHNIQUES

The most widely used approach for estimating recharge is the CMB technique, in both unsaturated and saturated zones. However, information on spatial and temporal variability in chloride deposition is usually limited, generally restricted to 1–3 years of data and often includes only wet deposition. Although uncertainties in recharge estimates vary linearly with uncertainties in chloride deposition, more emphasis should be placed on development of long-term records of wet and dry chloride deposition in (semi-) arid regions worldwide. Prebomb ^{36}Cl/Cl ratios have been used to estimate long-term chloride deposition at various sites (Phillips *et al*., 1988; Scanlon, 1991). Relationships between chloride deposition and distance from the coast have been developed for regions in Australia (Hutton, 1976). More data on chloride deposition should reduce uncertainties in recharge estimates based on this approach.

Historical tracers, such as bomb-pulse tritium and chlorine-36, have proved useful in delineating preferential flow in many regions (Nativ *et al*., 1995; de Vries *et al*., 2000; Flint *et al*., 2002). In some studies, much deeper penetration of tritium relative to chlorine-36 has been attributed to vapour transport; however, previous studies have shown that vapor diffusion of tritium is limited by equilibration of liquid and gas phases because the concentration of tritium is 5 orders of magnitude greater in the liquid than in the gas phase (Smiles *et al*., 1995). The liquid phase therefore acts as a large sink for tritium. Use of chlorine-36 to delineate preferential flow is also limited by damping of the bomb-pulse signal where high chloride concentrations occur in the matrix (Scanlon, 2000). Tritium has been widely used as an applied tracer in recharge studies in India. Most of these tracer studies represent a single monsoon season (Rangarajan and Athavale, 2000). The relatively short timescale of these experiments may not be representative of long-term mean recharge rates.

Most recharge studies described in this review relied heavily on environmental tracers; however, monitoring physical parameters, such as soil matric potential or groundwater levels, provides valuable information on flow processes for the duration of the monitoring periods. For example, matric potential profiles in the SW US provide important information on direction of water movement (Andraski, 1997; Scanlon and Goldsmith 1997). Monitoring matric potential in different settings has also been useful in delineating recharge processes related to inter-annual climate variability and LU/LC changes (Scanlon *et al*., 2005b). Matric potential monitoring has been limited mostly to the SW US and should be extended to (semi-) arid regions globally.

Modelling is the only technique that can be used to predict future recharge rates and is invaluable for isolating impacts of different controls on groundwater recharge (Salama *et al*., 1999; Zhang *et al*., 1999; Keese *et al*., 2005). The recharge rates compiled in this review will be valuable when compared with model results. Future work will probably include much more modelling analyses to assess management options in order to control groundwater recharge (either increase or decrease recharge). Such modelling analyses are currently being conducted in Australia to determine land management approaches to decreasing recharge and associated dryland salinity problems (Salama *et al*., 1999; Zhang *et al*., 1999). Types of models include land atmosphere, watershed, unsaturated zone, and groundwater models, and they can represent a range of scales from point to regional. It will be important for these simulations to include dynamic vegetation and two-way coupling between vegetation and the water cycle because both play critical roles in controlling soil water balance and, ultimately, deep drainage and recharge (Foley *et al*., 2000).

As many previous reviews on recharge have concluded, it is important to use a variety of different approaches to quantify recharge because various techniques complement each other in the range of space and time scales that they cover. Factors contributing to recharge in arid and semiarid environments often include variable precipitation, topography, soil depth, and quite often a thick unsaturated zone with variable properties. These factors contribute to a spatially variable influence on the timing of recharge to the saturated

DOI: 10.1002/hyp

zone, from less than a year to thousands of years, and, as a result, reinforce the need to use careful consideration of spatial and temporal scales in selecting approaches used to characterize the recharge or in evaluating or interpreting recharge data.

IMPLICATIONS FOR GROUNDWATER RESOURCE MANAGERS

Global compilation and evaluation of recharge rates have important implications for groundwater resource managers. Many natural ecosystems are characterized by low recharge rates or by discharge through ET, as in areas of eucalyptus mallee vegetation in Australia or inter-stream basins in the SW US. Cultivation has greatly increased recharge relative to that beneath natural ecosystems in many deserts. Increased recharge was recorded beneath dryland agriculture in areas of Africa, N. America, and Australia. These increased recharge rates indicate that future conversion of natural ecosystems to dryland agricultural ecosystems could result in increased water resources in desert systems. Recharge beneath irrigated agriculture increases with irrigation application amounts; however, such increases are generally masked by large groundwater level declines caused by irrigation pumpage. Irrigated agriculture is not sustainable in most desert systems, as shown by large groundwater level declines. Increasing efficiency of irrigation systems may improve water conservation if the increased efficiency is not accompanied by expansion of irrigated areas, as seen in parts of the High Plains in the United States (McMahon *et al.*, 2003). However, Foster *et al.* (2004) warned against 'double water resource accounting' because irrigation return flow would ultimately return to the aquifer and could be recovered. In contrast, dryland or rain-fed agriculture is likely to be sustainable because of generally moderate recharge rates in these regions relative to water use.

Another issue for water resource managers is how climate variability or climate change will impact groundwater recharge and how we can quantify such impacts. Recharge studies evaluated in this paper indicate that increased winter precipitation related to ENSO in the SW US should not alter recharge in inter-stream desert basins because of negative feedback related to increased vegetation productivity in these regions (McCabe and Dettinger, 1999; Scanlon *et al.*, 2005a). In contrast, elevated winter precipitation enhances stream flow in these regions, which results in focussed recharge beneath streams in desert basins (Redmond and Koch, 1991; Cayan and Webb, 1992; Pool, 2005). Therefore, monitoring stream flow related to ENSO can be used to predict impacts of ENSO on recharge. System response to decadal-scale variations in climate (droughts and floods) in parts of Africa was archived in unsaturated zone chloride profiles and indicates a direct relationship between precipitation and recharge in these settings (Edmunds and Tyler, 2002). Relationships between millennial-scale changes in climate (glacial interglacial cycles) and recharge are recorded in unsaturated zone chloride and matric potential profiles in the SW US and indicate a large decrease in recharge related to the shift from Pleistocene pluvial climate to Holocene arid climate, which is enhanced by the vegetation shift from mesic to xeric (Scanlon, 1991; Phillips, 1994; Tyler *et al.*, 1996). The insights provided by these studies can be applied to predicting impacts of future climate variability and change on groundwater recharge.

The ultimate goal would be to predict recharge rates related to global environmental change, including climate change and LU/LC changes. The compilation of recharge rates and understanding of recharge processes provided by this synthesis can be used to assess simulated recharge responses to projected climate and LU/LC changes. Regional climate models nested within global climate models can provide climate forcing. Land atmosphere models that incorporate dynamic vegetation can be used to provide real-time estimates of groundwater recharge and projections of future recharge in response to different climate and LU/LC change scenarios.

Water quality issues also affect water resources. Previous studies indicate that increased recharge related to conversion of natural to agricultural ecosystems has resulted in large-scale groundwater contamination caused by flushing of salts, such as chloride and nitrate, which had accumulated in the unsaturated zone. This mobilization of salts is critical for groundwater quality in many areas, particularly Australia, where extensive groundwater and surface water salinization has resulted from dryland agriculture (Allison *et al.*, 1990; Cook *et al.*, 2001). Nitrate mobilization is critical in the US High Plains, where a large fraction of the

DOI: 10.1002/hyp

wells exceed the maximum contaminant level of 10 mg l^{-1} NO_3-N. Therefore, if conversion of rangeland to dryland agriculture is being considered to increase recharge, the reservoir of stored salts in the rangeland setting should be characterized to assess potential impacts on groundwater quality.

SUMMARY

- Average recharge rates estimated over large areas (40–374 000 km^2) range from 0·2 to 35 mm $year^{-1}$, representing 0·1 to 5% of long-term average annual precipitation.
- Focussed recharge beneath ephemeral streams and lakes and preferential flow mostly in fractured rock result in highly variable recharge rates, up to 720 m $year^{-1}$.
- The CMB approach is the most widely used technique for estimating recharge; however, information on spatial and temporal variability in chloride input is limited, and monitoring of chloride input needs to be expanded.
- Impacts of climate variability and LU/LC changes are archived in unsaturated zone tracer profiles and groundwater level fluctuations.
- Climate variability at inter-annual timescales related to elevated precipitation and increased streamflow associated with ENSO results in increased recharge in Arizona, California, and Argentina, as shown by rising water tables. Recharge increased by up to a factor of 3 in Arizona (US). Inter-stream recharge is unlikely, as shown by negative feedback provided by biomass productivity in Nevada (US).
- Climate variability at decadal timescales results in variations in recharge by a factor of 5 in Africa, related to drought and non-drought periods.
- Variations in paleoclimate at millennial timescales changed systems from recharge during the Pleistocene pluvial period to discharge during the Holocene semiarid period in the SW US. Recharge in N. Africa also occurred during the Pleistocene and was generally restricted to river channels during the Holocene.
- LU/LC changes related to deforestation have increased recharge by up to about 2 orders of magnitude in Australia and flushed salts into underlying aquifers and adjacent streams.
- Changes from natural grasslands and shrublands to cultivated ecosystems have altered systems from discharge (ET) to diffuse recharge ($\sim$24 mm $year^{-1}$) in the SW US, related to fallow periods. Cultivation increased surface runoff and focussed recharge in endoreic ponds in the Great Plains (N. America) and in Niger (Africa).
- Impact of LU/LC changes exceeds that of climate variability in Niger, as shown by order-of-magnitude increases in recharge, even during severe drought periods.
- Recharge in irrigated areas ranges from 10 to 485 mm $year^{-1}$ (1–25% of irrigation + precipitation); however, pumpage in groundwater-irrigated systems greatly exceeds recharge, resulting in large water level declines in irrigated areas (China, United States, Europe)
- Sensitivity of recharge to LU/LC changes indicates that such changes may be managed in the future to control recharge.
- The compilation of recharge rates in this study and understanding of impacts of past climate and LU/LC changes are critical to sustainable development of water resources within the context of climate variability and LU/LC changes.

ACKNOWLEDGMENTS

The motivation for this recharge review study originated at a meeting related to global mapping of groundwater recharge organized by Dr Bill Wallin at the International Atomic Energy Agency in Vienna in 2005. We would like to acknowledge financial support for this study from the Jackson School of Geosciences. The authors benefited from discussions with individuals on their recharge studies. Reviews by Brent Newman (Los Alamos National Laboratory) and an anonymous reviewer greatly improved the paper.

APPENDIX

Appendix I. Recharge estimates using a variety of methods

	Reference	Country/Region	Method	# Sites	Area (km^2)	P(mm year^{-1})	R(mm year^{-1})	Additional information
SW North America								
1	Prych, 1998; Fayer *et al*., 1996	Hanford, WA	CMB_{UZ}	4		160	0·01–0·11	Silt loam, sagebrush and grasses
			^{36}Cl	2			≤2·1, ≤3·4	
1	Prych, 1998; Fayer *et al*., 1996	Hanford, WA	CMB_{UZ}	5		160	0·01–0·3	Loam, sand and gravel, sagebrush and grasses
			^{36}Cl	1			≤2·6	
1	Prych, 1998; Fayer *et al*., 1996	Hanford, WA	CMB_{UZ}	4		160	0·4–2·0	Loamy sand, sand, grass
			^{36}Cl	1			5·1	
1	Fayer *et al*., 1996	Hanford, WA	WB (lysimeter, 8-year)	1		160	55·4	No veg., medium-coarse sand
1	Fayer *et al*., 1996	Hanford, WA	WB (lysimeter, 3-year)	2		184, 480	86·7, 300	No veg., gravel—sand—gravelly sand
1	Fayer *et al*., 1996	Hanford, WA	WC monitoring (8-year)	1		160	5·6–53·1 (25·4)	Grass, loamy-coarse sand
1	Fayer *et al*., 1996	Hanford, WA	GIS		765	160	11	Various veg. and soil combinations
2	Flint *et al*., 2004	Great Basin, NV	WB model (34-year)		374,218	50–1700 (280)	9·7	Assuming 10–90% (S-N) Ro becomes R
3	Flint and Flint, in press	Great Basin, NV	WB model (30-year)		374 218	50–1700 (280)	0–1300 (16·9)	Total potential R (100% Ro becomes R)
4	Flint and Flint, in press	SW US	WB model (30-year)		1 039 647	51–1931 (301)	0–1612 (11·2)	Total potential R (100% Ro becomes R)
5	Flint and Flint, in press	Death Valley, CA and NV	WB model (30-year)		45 288	50–552 (171)	1·7	Total potential R (100% Ro becomes R)

(*continued overleaf*)

Appendix I. (*Continued*)

	Reference	Country/Region	Method	# Sites	Area (km^2)	P(mm $year^{-1}$)	R(mm $year^{-1}$)	Additional information
6	Hevesi *et al.*, 2003	Death Valley, CA and NV	WB model (50-year)		45 288	50–552 (171)	0–>500 (2·8)	Closed basins, playa lakes; shrubs, woodlands, and forests
7	Stonestrom *et al.*, 2004	Amargosa Desert, NV	CMB_{UZ}	2		108	41, 91	Ephemeral stream
			Cl disp.	1			70	
8	Prudic, 1994	Amargosa Desert, NV	CMB_{UZ}	3		100	2*	Rangeland
9	Flint *et al.*, 2001	Yucca Mtn, NV	WB model (multiple spatial and temporal scales)			130–280 (170)	0–>80 (5–10)	Fracture and piston flow
10	Flint *et al.*, 2002	Yucca Mtn, NV	CMB_{UZ}	6	~60	170	<0·01–9·9	Deep alluvium—volcanic tuffs
			CMB_{SZ}	6			8·5	
10	Flint *et al.*, 2002	Yucca Mtn, NV	CMB_{SZ}			170	8–15*	SZ data from perched aquifer
10	Flint *et al.*, 2002	Yucca Mtn, NV	WC monitoring (11-year)	69		170	10–30 (11·6)	Lowlands to uplands
11	Scanlon *et al.*, 2005b	Amargosa Desert, NV	CMB_{UZ}	1		113	0·5*	Rangeland, sands and gravels
11	Scanlon *et al.*, 2005b	Amargosa Desert, NV	CMB_{UZ}	6		113 (2000–2700 irr)	130–640	Irr. ag., sands and gravels
			Cl, NO_3 disp.	4			150–280	
12	Tyler *et al.*, 1992	NTS, NV	^3H	1		125	0	Undisturbed
12	Tyler *et al.*, 1992	NTS, NV	^3H	1		125	~600	Subsidence crater, coarse sediments
13	Tyler *et al.*, 1996	NTS, NV	CMB_{UZ}	3		29–230 (124)	4·4*, 5·9*, 7·6*	Alluvial deposits, shrubs
14	Izbicki, 2002	Mojave Desert, CA	UZ model (100-year)	1		≤150	1300	Ephemeral stream, alluvial fan deposits
15	Nimmo *et al.*, 2002	Mojave Desert, CA	UG	3		≤150	20–60	Ephemeral stream low rates—lateral spreading at depth
16	Prudic, 1994	Ward Valley, CA	CMB_{UZ}	3		150	0·03–0·05*	Rangeland

17	Manning and Solomon, 2004	Wasatch Mtns., UT	^{3}H/He dating	53	∼300	500–1300	∼210	Total R
17	Manning and Solomon, 2004	Wasatch Mtns., UT	Noble gases	66		500–1300	>63–∼210	Mountain-block R (≥30% of total)
18	Heilweil *et al.*, 2006	Sand Hollow, UT	^{3}H	7			2·6–>57	Sandstone and sandy soil
			CMB_{UZ}	13	50	210	0·5–13 (4)	
			CMB_{SZ}	31			3–60 (11)	
19	Zhu, 2000	AZ	GC model (^{14}C/GW);	51	14 000	<300–320 (305)	13–19*	Grass shrub—piñon-juniper
			CMB_{SZ}	51			5–20 (16)	
20	Goodrich *et al.*, 2004	AZ	Micro-gravity	4			4·1	Rangeland, clays and silts—conglo-merates
			CMB_{UZ}	1	112	324	2·9	
			CMB_{SZ}	21			1·9	
21	Newman *et al.*, 1997	NM	CMB_{UZ}	22		510	0·2	Clay-rich horizon, ponderosa pine forest
21	Newman *et al.*, 1997	NM	CMB_{UZ}	6		470	2	Not as clay rich, piñon-juniper wood
22	Sanford *et al.*, 2004	MRGB, NM	GW model (^{14}C, WTF; steady state)	200	7900	218–483 (272)	8·5	
				200				
23	Anderholm, 2001	MRGB, NM	CMB_{SZ}	9	1570	343–538 (456)	2·5–46 (8·7)	Mountain-front R
24	Constantz and Thomas, 1996	NM	Temperature	1		∼350	∼720, 000	Ephemeral stream
25	Phillips *et al.*, 1988	NM	CMB_{UZ}	2			2·0, 2·5	Sandy loam–fine sand, creosote/saltbush
			^{36}Cl	2		200	2·6, 3·0	
			^{3}H	1			8·4	
26	Stephens and Knowlton, 1986	NM	Pressure head UG	1		200	7–37	Ephemeral stream, sand, sparse saltbush
				1			37	
27	Phillips *et al.*, 1988	NM	CMB_{UZ}	1			1·5	Sandy loam-sandy clay loam, grass and shrubs
			^{36}Cl	1		230	2·5	
			^{3}H	1			9·5	

(*continued overleaf*)

DOI: 10.1002/hyp

Appendix I. (*Continued*)

	Reference	Country/Region	Method	# Sites	Area (km^2)	P(mm $year^{-1}$)	R(mm $year^{-1}$)	Additional information
28	Gee *et al*., 1994	NM	WB (lysimeter, 8-year)	1		230	87	Loamy fine sand and silty clay loam, no veg.
29	Roark and Healy, 1998	Roswell Basin, NM	WB	2		356 (958, 1698 irr.)	150, 380	Irr. ag., alfalfa
30	Keese *et al*., 2005	TX	UZ model (30-year)	3	1152–14 980	224–380	0·2, 1·5, 11·1	Arid locations, coarse soils, shrubland
31	Scanlon, 1991	Hueco Bolson, TX	CMB_{UZ}	3	40	110–430 (280)	0·07*, 0·07*, 0·08*	Inter-stream, clay to muddy-sandy-gravel
31	Scanlon, 1991	Hueco Bolson, TX	CMB_{UZ}	3		110–430 (280)	0·13, 0·19, 0·60	Ephemeral stream, clay to muddy-sandy-gravel
32	Scanlon, 1992	Hueco Bolson, TX	^{36}Cl	1		110–430 (280)	<1·4	Ephemeral stream, clay to muddy-sandy-gravel
			^{3}H	1			<7	
33	Scanlon *et al*., 1999, 2000	Eagle Flat, TX	CMB_{UZ}	34	60	320	0·01–0·16* (0·05)*	Interdrainage, fine soils, grasses, yucca and mesquite
33	Scanlon *et al*., 1999, 2000	Eagle Flat, TX	CMB_{UZ}	10	60	320	<0·2–>3·8	Drainage (excludes runon)
33	Scanlon *et al*., 1999, 2000	Eagle Flat, TX	CMB_{UZ}	6	60	320	<1·5–>13·4	Fissure/gully/pit (excludes runon)
34	Keese *et al*., 2005	TX	UZ model (30-year)	8	1152–2474	474–855	0·4–35·1	semiarid locations, variable soils, crops, grasses, shrubs, trees
35	Scanlon *et al*., 2005b	SHP, TX	CMB_{UZ} WTF	4	3400	457	9, 12, 25, 32 4–57 (24)	Dryland ag, sands
36	McMahon *et al*., 2006	SHP, TX	^{3}H	2		440, 484 (450, 330 irr)	17, 32	Irr. ag.
37	Scanlon *et al*., 2005b	SHP, TX	CMB_{UZ}	2		457–500	0·5–2*	Rangeland
38	Wood and Sanford, 1995	SHP, TX	CMB_{SZ}	3071	80 000	330–560 (485)	11	Playas
			^{3}H	1			77	
39	Scanlon and Goldsmith, 1997	SHP, TX	CMB_{UZ}	9		500	60–100	Playa, clay underlain by sand
			^{3}H	1			120	
39	Scanlon and Goldsmith, 1997	SHP, TX	CMB_{UZ}	13		500	≤0·1–4*	Interplaya rangeland

40	McMahon *et al.*, 2003	CHP, KS	CMB_{UZ}	1			5·1	Rangeland, loamy fine sand
			^{3}H (mass bal.)	1		453	4·4	
			^{3}H (interface)	1			5·4	
41	McMahon *et al.*, 2003	CHP, KS	Cl disp.	1		487 (700, 650 irr)	53	Irr. ag., sand and loam
			^{3}H (mass bal.)	2			21, 34	
			^{3}H (interface)	2			39, 54	
			^{3}H (pref. flow)	2			106, 116	
42	Sophocleous, 1992	CHP, KS	WTF	10	10 260	458–729 (562)	0–177 (56)	Sand dune prairie environment
			GIS				36	
43	Szilagyi *et al.*, 2005	NE	WB model (GIS, 30-year)		200 500	350–915	3–163	Entire state (SW–E)
Central/South America								
44	Edmunds, 2001	Mexico	CMB_{UZ}	1		230	0·1, 0·5*	Alluvial sediments
45	Mahlknecht *et al.*, 2004	Mexico	CMB_{SZ}	246	6840	<400–>800	10–>800 (25)	Plains (min) mountains (max)
46	Birkle *et al.*, 1998	Mexico	WB		9600	746	96–149	Natural veg. and ag., volcanics
47	Halm *et al.*, 2002	Brazil	WB model (2-year)			700	6, 7	Drought deciduous shrub, sand
47	Halm *et al.*, 2002	Brazil	WB model (2-year)			700	13, 16	Cassava crop, sand
Africa								
48	Edmunds, 2001	Tunisia	CMB_{UZ}	6		100	1·3	Sand, natural veg.
49	Gaye and Edmunds, 1996	Senegal	CMB_{UZ}	2	0·1	220–350 (290)	29, 34	Sand, dryland ag.
			^{3}H	2			22, 26	
50	Edmunds and Gaye, 1994	Senegal	CMB_{UZ}	13	1600	220–350 (290)	0·5–34	Thick sands-clays, 40% cleared
			CMB_{SZ}	119			1–20	
51	Cook *et al.*, 1992a	Senegal	CMB_{UZ}	19		356	15	Dryland ag.
52	Favreau *et al.*, 2002b	Niger	Model based on WTF, ^{14}C, ^{3}H (10-year)	33	3500	567	1–5	Pre-clearing, woodland, savanna
53	Leduc *et al.*, 2001	Niger	^{14}C	45			3	Savanna, tiger bush, crops
			^{3}H	45	8000	565	6	
			WTF				10–47 (20)	

(*continued overleaf*)

Appendix I. (*Continued*)

	Reference	Country/Region	Method	# Sites	Area (km^2)	P(mm $year^{-1}$)	R(mm $year^{-1}$)	Additional information
54	Bromley *et al.*, 1997	Niger	CMB_{UZ}	1		564	13	Tiger bush (banded woodland and bare soil)
			CMB_{SZ}	1			28	
55	Edmunds *et al.*, 1999	Nigeria	CMB_{UZ}	5	30 000	434	15–54	Grasslands, interdune lakes and playas
			CMB_{SZ}	340			60	
56	Edmunds *et al.*, 1988	Sudan	CMB_{UZ}	13	6	200	0·3–1·3 (0·7)	Interfluvial sandy clay
56	Edmunds *et al.*, 1988	Sudan	CMB_{UZ}	1		200	5·8	Sandstone ridge, possible surface runoff
57	Selaolo *et al.*, 1996	Botswana	CMB_{UZ}	2			0·5	
			Isotope disp.	2		400	1·1	
			^{3}H	2			3·8	
58	de Vries *et al.*, 2000	Botswana	CMB_{UZ}	∼50	4875	420	1–10 (3)	Sand, savanna, level areas
			CMB_{SZ}				7	
58	de Vries *et al.*, 2000	Botswana	CMB_{UZ}	1		420	50	Depression
58	de Vries *et al.*, 2000	Botswana	CMB_{UZ}	1		<400	0·6	Sand, savanna
			CMB_{SZ}	2			1·2	
59	Gieske *et al.*, 1995	Botswana	CMB_{UZ}	1		∼420	14–22	Shrubs and grasses, fine sand
			^{3}H	1			9	
60	Selaolo *et al.*, 1996	Botswana	CMB_{UZ}	20		500	11	Valley
			^{3}H				16	
61	Butler and Verhagen, 2001	S. Africa	CMB_{UZ}	2			1·8, 5	Sand, savanna
			CMB_{SZ}	3		336	3·7, 3·8, 9·9	
			^{3}H	2			13	
62	Sami and Hughes, 1996	S. Africa	CMB_{SZ}	12	665	460	0–8 (4·5)	Grassland, loams, fractured rock
			SS model (35-year)			483	5·8	
Middle East								
63	Edmunds *et al.*, 1988	Cyprus	$CMB_{UZ,}$	7	6	406	33–94	Fine sand, sparse veg.
			^{3}H	5			22–75	
64	Nativ *et al.*, 1995	Israel	^{3}H	4		200	16, 26, 41, 66	Fractured chalk
			Bromide	3			30, 50, 110	
65	Edmunds, 2001	Jordon	CMB_{UZ}	1		480	28	Sandstones
66	Subyani, 2005	Saudi Arabia	CMB_{SZ}	13	1600	100–220	20	Ephemeral stream

67	Subyani, 2004	Saudi Arabia	CMB_{SZ}	26	400	450	6·1	Ephemeral stream
68	Bazuhair and Wood, 1996	Saudi Arabia	CMB_{SZ}	1422	135 000	160	3·7	Alluvial aquifers
69	Dincer *et al*., 1974	Saudi Arabia	^3H	1	25 000	70	20	Sand dunes
70	Sanford and Wood, 2001	UAE	WB		~3000	50–90	64	Salt flat, fine sand (R lost to E during dry season)
India								
71	Navada *et al*., 2001	N. India	CMB_{UZ}	4		240	9·6, 12, 14·5, 18	Dryland ag., sand, calcrete, gravel, clay
72	Sukhija *et al*., 2003	N. India	^3H (Injected)	3		~740	13–66	Alluvium
73	Rangarajan and Athavale, 2000	India	^3H (Injected)	9		460–1004	46–161	Variable
74	Sukhija *et al*., 2003	C. India	CMB_{UZ}	4		~725	20–40	Fractured granites
			CMB_{SZ}	4			70–170	
75	Sukhija *et al*., 2003	S. India	CMB_{UZ}	3		~1004	170–300	Semi-consolidated sandstone
			CMB_{SZ}	3			260–440	
China								
76	Wang *et al*., 2004a	Tengger Desert	WB (lysimeter)	1		88–496 (191)	48	No veg.
77	Ruifen and Keqin, 2001	Shanxi Prov.	CMB_{UZ}	1			288	Loess
			CMB_{SZ}	1		550	113	
			^3H	2			48–68	
78	Kendy *et al*., 2003	N. China Plain	WB model (3-year)	16		367 (68–482 irr)	36–209	Irr. ag., winter wheat, maize; loam
79	Kendy *et al*., 2004	N. China Plain	WB model (52-year)	12	400	461 (0–1200 irr)	50–1090	Irr. ag., winter wheat, maize; loam
80	Jin *et al*., 2000	Hebei Plain	^3H (Injected)	8	51	534	92–243	Irr. ag., variable soils and cultivation practices
81	Ruifen and Keqin, 2001	Inner Mongolia	CMB_{UZ}	1			85	Loess
			CMB_{SZ}	1		360	87	
			^3H	2	—	—	40–47	
Australia								
82	Salama *et al*., 1993	West	CMB_{SZ}	2		339–494 (409)	0·4–1	Pre-clearing

(*continued overleaf*)

Appendix I. (*Continued*)

	Reference	Country/Region	Method	# Sites	Area (km^2)	P(mm year^{-1})	R(mm year^{-1})	Additional information
82	Salama *et al.*, 1993	West	Cl disp.	2		409	10	Post-clearing
83	Harrington *et al.*, 2002	Central	^{14}C	7	600	290	1·9	Ephemeral stream (center of basin)
83	Harrington *et al.*, 2002	Central	^{14}C	35	4900	290	~0·2	Rest of basin
83	Harrington *et al.*, 2002	Central	CMB_{SZ}	42	5500	120–460 (290)	0·1–2 (0·8)	Entire basin
84	Love *et al.*, 2000	Central	CMB_{SZ}	21	~47 000	170–220 (200)	0·08–0·24	Fine sand and silcrete
85	Allison *et al.*, 1985 (Murkbo site)	South	CMB_{UZ}	1		300	0·1, 0·17*	Calcrete, eucalyptus, shrubs, grasses
85	Allison *et al.*, 1985 (Murkbo site)	South	CMB_{UZ}	1		300	0·09, 0·07*	Primary sinkhole, bush
85	Allison *et al.*, 1985 (Murkbo site)	South	CMB_{UZ}	1		300	>60	Secondary sinkhole, shrubs, grasses
			^{3}H	1			>100	
85	Allison *et al.*, 1985, (Murkbo site)	South	CMB_{UZ}	2		300	0·06	Mallee, dune
85	Allison *et al.*, 1985 (Murkbo site)	South	Cl disp.	1		300	13–14	Cleared dune
86	Cook *et al.*, 1994 (Murkbo site)	South	CMB_{UZ}	1		260	0·1	Mallee, sand
			^{36}Cl	1			0·9	
87	Leaney and Allison, 1986	South	CMB_{SZ}	130	10 000	250–300	0·25	Natural veg.; sand, clay, silt
			^{14}C	33			0·1–0·2	
88	Cook *et al.*, 2004	South	Cl disp.	14		260	0·1–14·8 (2·7)	Cleared, dryland ag. [1]regionalization based on soil texture
			GIS[1]		~3000		1–14·8 (4·9)	
89	Allison *et al.*, 1990 (Maggea site)	South	CMB_{UZ}	5		250–450	0 · 04–0·09	Mallee
89	Allison *et al.*, 1990 (Maggea site)	South	Cl disp.	6		250–450	<1–9	Cleared
90	Cook *et al.*, 1989 (Borrika site)	South	Cl disp.	8	0·14	340	5–>33	Cleared, crops/pasture
			EMI				2·7	
90	Cook *et al.*, 1989 (Borrika site)	South	CMB_{UZ}	4		340	0·4–0·6	Mallee wood, sand

91	Cook *et al.*, 1994 (Borrika site)	South	Cl disp.	5			4–28	Cleared, crops/pasture
			^{3}H	3		340	8, 13, 17	
			^{36}Cl	2			11	
92	Cook *et al.*, 1992b (Borrika site)	South	Cl disp.	12	0·14	340	1–14 (~5)	Cleared, dryland ag. sand-sandy loam
93	Cook and Kilty, 1992 (Borrika site)	South	EMI	20	32	340	<1–>50	Mostly cleared, dryland farming
94	Allison *et al.*, 1990 (Kulkami site)	South	CMB_{UZ}	9		250–450	0·06–0·08	Mallee, sand
94	Allison *et al.*, 1990 (Kulkami site)	South	Cl disp.	14		250–450	<5–>51	Cleared, sand
95	Barnett, 1989	South	^{14}C			250–450	0·1–0·2	Pre-clearing of mallee
95	Barnett, 1989	South	CMB_{UZ}			250–450	8–40	Cleared mallee
96	Allison and Hughes, 1983	South	CMB_{UZ}	4		335	0·07	Mallee, sand/sandy loam
96	Allison and Hughes, 1983	South	Cl disp.	8		335	3–4	Cleared mallee, wheat, sand/sandy loam
97	Leaney and Herczeg, 1995	South	CMB_{UZ}		3000	490–600	0·5	Pre-clearing
97	Leaney and Herczeg, 1995	South	CMB_{UZ}		1750	490–600	<4–>40	Post-clearing, clay-sand, little irr.
97	Leaney and Herczeg, 1995	South	CMB_{UZ}		1250	490–600 (400–500 irr)	10	Irr. ag., clay
98	Zhang *et al.*, 1999	Southeast	EH model (3-year)		1·6	~560	~28 (5%P)	Pastoral Catchment

Country/Region: WA, Washington State; NV, Nevada; SW US, south-west United States; CA, California; NTS, Nevada Test Site; UT, Utah; AZ, Arizona; NM, New Mexico; MRGB, Middle Rio Grande Basin; TX, Texas; SHP, Southern High Plains; CHP, Central High Plains; KS, Kansas; NE, Nebraska; UAE, United Arab Emirates. Methods: ^{14}C, Carbon-14 as a tracer; ^{36}Cl, Chlorine-36 tracer; ^{3}H, tritium tracer; $^{3}H/He$ dating, tritium-helium dating; Bromide, bromide tracer; CMB_{SZ}, saturated zone Chloride Mass Balance; CMB_{UZ}, unsaturated zone Chloride Mass Balance; disp., tracer displacement (Cl, NO_3, isotope); EH model, Ecohydrological model; EMI, Electromagnetic Induction survey; GC model, Geochemical model; GIS, Geographic Information Systems (regionalization of data); GW model, Groundwater model; Micro-gravity, micro-gravity survey; Noble gases, provide information on recharge temperature; Pressure head, Darcy's equation (pressure head and unit gradient; SS model, Surface–Subsurface model; Temperature, temperature monitoring and modelling; UG, Darcy's law with unit gradient; UZ model, Unsaturated zone model; WB model, water balance model; WB, water balance measurements; water balance based on water content; WTF, water-table fluctuations. P, precipitation; R, calculated recharge (mean and/or range) from method listed, * indicates Pleistocene recharge rates, values in parentheses indicate an average rate. Additional Information: Ro, runoff; E, evaporation; SZ, saturated zone; veg., vegetation; irr. ag., irrigated agriculture; S, south; N, north; E, east; C, central; SW, south-west.

DOI: 10.1002/hyp

Appendix II. Recharge estimates based on Chloride Mass Balance (CMB) approach

Ref.	Country/region	# Sites	Area km^2	P mm $year^{-1}$	Cl_P mg l^{-1}	Cl_{sz} mg l^{-1}	R_{SZ} mm $year^{-1}$	Cl_{UZ} mg/l	R_{UZ} mm $year^{-1}$	Additional information
SW North America										
7	NV	2	—	108	37^1, 102^1	—	—	97, 121	41, 91	Ephemeral stream; [1]Includes Cl from runon
10	NV	6 SZ	60	170	0·35	7	8·5	6–7400	<0·01–9·9	Deep alluvium—volcanic tuffs
—	—	6 UZ	—	—	—	—	—	—	—	—
13	NV	3		186 (124* 150%)	0·56			23·7, 17·9, 13·9	4·4*, 5·9*, 7·6*	Alluvial deposits, shrubs
23	NM	9	1570	539–368	0·3	3·5–45	2·5–46	—	—	Mountain-front recharge
38	TX	3071	80 000	485	0·58	25·2	11			Playas
Africa										
49	Senegal	2	0·1	290	2·8	—	—	24, 28	29, 34	Sand, dryland agriculture
50	Senegal	119 SZ	1600	290	2·8	41–812	1–20	24–1660	0·5–34	Thick sands-clays, 40% cleared
—	—	13 UZ	—	—	—	—	—	—	—	—
55	Nigeria	340 SZ	30 000	434	1·43	10·3	60	11·5–41·6	15–54	Grasslands, interdune lakes and playas
—	—	5 UZ	—	—	—	—	—	—	—	—
56	Sudan	13	6	200	5			783–3936	0·3–1·3	Interfluvial sandy clay
56	Sudan	1		200	5			173	5·8	Sandstone ridge, possible surface runoff

DOI: 10.1002/hyp

58	Botswana	~50	4 875	420	1·19	75	7	50–500	1–10	Sand, bush and tree savanna
61	S. Africa	3 SZ		336	1	34, 88, 90	3·7, 3·8, 9·9	80, 200	5, 1·8	Sand, savanna
—	—	2 UZ	—	—	—	—	—	—	—	
Middle East										
63	Cyprus	7	6	406	16·26	—	—	70–200	33–94	Fine sand, sparse veg.
65	Jordan	1		480	10·2	—	—	173	28	Sandstones
68	Saudi Arabia	1422	135, 000	160	9	391	3·7	—	—	Alluvial aquifers
India										
71	N. India	4		240	2	—	—	26·5, 33, 39·3, 50	9·6, 12, 14·5, 18	Dryland agriculture, sand, calcrete, gravel, clay
China										
77	Shanxi Prov.	1		550	10·2	49·7	113	19·5	288	Loess
81	Inner Mongolia	1	—	360	2·2	9·1	87	9·3	85	Loess
Australia										
82	W. Aust	2	—	409	4·9	2000–5000	0·4–1	—	—	Pre-clearing
83	C. Aust	42	5500	290	0·5	71–1240	0·1–2 (0·8)	—	—	Basin/flood plain
84	C. Aust	21	~47 000	200	0·625	530–1620	0·08–0·24	—	—	Fine sand and silcrete
85	S. Aust	1	'Murkbo'	300	4·3	—	—	7500	0·17*	Calcrete, eucalyptus, shrubs, grasses
85	S. Aust	2		300	4·3	—	—	20 000	0·06	Mallee dune
86	S. Aust	1	'Murkbo'	260	3·8	—	—	14 000	0·1	Mallee, sand
96	S. Aust	1		335	2·3	—	—	11 600	0·07	Mallee, sand/sandy loam
97	S. Aust		3000	500	6·6	—	—	6000	0·5	Pre-clearing

Ref., reference numbers—refer to Appendix I; P, mean annual precipitation; Cl_p, concentration of Cl in precipitation; Cl_{sz}, measured Cl concentration in saturated zone; R_{sz}, recharge calculated by CMB applied to saturated zone Cl data; Cl_{uz}, measured Cl concentration in unsaturated zone; R_{uz}, recharge calculated by CMB applied to unsaturated zone Cl data. * Indicates Pleistocene recharge rates.

REFERENCES

Allison GB, Hughes MW. 1983. The use of natural tracers as indicators of soil-water movement in a temperate semi-arid region. *Journal of Hydrology* **60**: 157–173.

Allison GB, Stone WJ, Hughes MW. 1985. Recharge in karst and dune elements of a semi-arid landscape as indicated by natural isotopes and chloride. *Journal of Hydrology* **76**: 1–26.

Allison GB, Cook PG, Barnett SR, Walker GR, Jolly ID, Hughes MW. 1990. Land clearance and river salinisation in the western Murray Basin, Australia. *Journal of Hydrology* **119**: 1–20.

Anderholm SK. 2001. Mountain-front recharge along the eastern side of the Middle Rio Grande Basin, Central New Mexico. USGS Water Resources Investigations Report 00–4010, 36.

Andraski BJ. 1997. Soil-water movement under natural-site and waste-site conditions: A multi-year field study in the Mojave Desert, Nevada. *Water Resources Research* **33**: 1901–1916.

Andrews JN, Fontes JC, Aranyossy JF, Dodo A, Edmunds WM, Joseph A, Travi Y. 1994. The evolution of alkaline groundwaters in the continental Intercalaire aquifer of the Irhazer-Plain, Niger. *Water Resources Research* **30**: 45–61.

Anyamba A, Eastman JR. 1996. Interannual variability of NDVI over Africa and its relation to El Nino Southern Oscillation. *International Journal of Remote Sensing* **17**: 2533–2548.

Athavale RN, Chand R, Rangarajan R. 1983. Groundwater recharge estimates for two basins in the Deccan Trap basalt formation. *Hydrological Sciences Journal-Journal Des Sciences Hydrologiques* **28**: 525–538.

Athavale RN, Rangarajan R, Muralidharan D. 1998. Influx and efflux of moisture in a desert soil during a 1 year period. *Water Resources Research* **34**: 2871–2877.

Barnett SR. 1989. The effect of land clearance in the Mallee region on River Murray salinity and land salinisation. *Journal of Australian Geology and Geophysics* **11**: 205–208.

Bazuhair AS, Wood WW. 1996. Chloride mass-balance method for estimating ground water recharge in arid areas: Examples from western Saudi Arabia. *Journal of Hydrology* **186**: 153–159.

Birkle P, Rodriguez VT, Partida EG. 1998. The water balance for the Basin of the Valley of Mexico and implications for future water consumption. *Hydrogeology Journal* **6**: 500–517.

Bromley J, Taylor CM, Gash JHC. 2002. Discussion–Comment on ‘Long-term rise in a Sahelian water-table: the continental terminal in South-West Niger’ by Leduc, C., Favreau, G., Schroeter, P., 2001. Journal of Hydrology 243, 43–54. *Journal of Hydrology* **255**: 260–262.

Bromley J, Cruces J, Acreman M, Martinez L, Llamas MR. 2001. Problems of sustainable groundwater management in an area of over-exploitation: The upper Guadiana catchment, central Spain. *International Journal of Water Resources Development* **17**: 379–396.

Bromley J, Edmunds WM, Fellman E, Brouwer J, Gaze SR, Sudlow J, Taupin JD. 1997. Estimation of rainfall inputs and direct recharge to the deep unsaturated zone of southern Niger using the chloride profile method. *Journal of Hydrology* **189**: 139–154.

Butler MJ, Verhagen BT. 2001. Isotope studies of a thick unsaturated zone in a semi-arid area of Southern Africa. In *Isotope Based Assessment of Groundwater Renewal in Water Scarce Regions*, Yurtsever Y (ed.). IAEA-Tecdoc-1246. IAEA: Vienna, 45–70.

Calder IR, Hall RL, Prasanna KT. 1993. Hydrological impact of eucalyptus plantation in India. *Journal of Hydrology* **150**: 635–648.

Cayan DR, Webb RH. 1992. El Nino/Southern oscillation and streamflow in the western United States. In *El Nino: Historical and Paleoclimatic Aspects of the Southern Oscillation*, Diaz HF, Markgraf V (eds). Cambridge University Press: London; 29–88.

Cayan DR, Redmond KT, Riddle LG. 1999. ENSO and hydrologic extremes in the western United States. *Journal of Climate* **12**: 2881–2893.

Constantz J, Thomas CL. 1996. The use of streambed temperature profiles to estimate the depth, duration, and rate of percolation beneath arroyos. *Water Resources Research* **32**: 3597–3602.

Constantz J, Stewart AE, Niswonger R, Sarma L. 2002. Analysis of temperature profiles for investigating stream losses beneath ephemeral channels. *Water Resources Research* **38**: 1316, DOI:10.1029/2001WR001221.

Cook PG, Kilty S. 1992. A helicopter-borne electromagnetic survey to delineate groundwater recharge rates. *Water Resources Research* **28**: 2953–2961.

Cook PG, Walker GR, Jolly ID. 1989. Spatial variability of groundwater recharge in a semiarid region. *Journal of Hydrology* **111**: 195–212.

Cook PG, Edmunds WM, Gaye CB. 1992a. Estimating paleorecharge and paleoclimate from unsaturated zone profiles. *Water Resources Research* **28**: 2721–2731.

Cook PG, Leaney FW, Jolly ID. 2001. Groundwater recharge in the Mallee Region, and salinity implications for the Murray River–A Review. CSIRO Publishing: Australia; CSIRO Land and Water Technical Report 45/01, 133.

Cook PG, Leaney FW, Miles M. 2004. Groundwater Recharge in the North-East Mallee Region, South Australia. CSIRO Publishing: Australia; CSIRO Land and Water Technical Report No 25/04, 80.

Cook PG, Jolly ID, Leaney FW, Walker GR. 1994. Unsaturated zone tritium and chlorine 36 profiles from southern Australia: Their use as tracers of soil water movement. *Water Resources Research* **30**: 1709–1719.

Cook PG, Walker GR, Buselli G, Potts I, Dodds AR. 1992b. The application of electromagnetic techniques to groundwater recharge investigations. *Journal of Hydrology* **130**: 201–229.

Darling WG, Edmunds WM, Kinniburgh DG, Kotoub S. 1987. *Sources of Recharge to the Basal Nubian Sandstone Aquifer, Butana Region, Sudan*. IAEA: Vienna; 205–224.

de Vries JJ, Selaolo ET, Beekman HE. 2000. Groundwater recharge in the Kalahari, with reference to paleo-hydrologic conditions. *Journal of Hydrology* **238**: 110–123.

Diechmann U, Eklundh L. 1991. Global digital datasets for land degradation studies: a GIS approach. *United Nations Environment Program/Global Resource Information Database*, *GRID Case Study Series No. 4*, UNEP/GEMS and GRID: Nairobi, Kenya.

Dincer T, Al-Mugrin A, Zimmermann U. 1974. Study of the infiltration and recharge through the sand dunes in arid zones with special reference to stable isotopes and thermonuclear tritium. *Journal of Hydrology* **23**: 79–109.

Doll P, Kaspar F, Lehner B. 2003. A global hydrological model for deriving water availability indicators: model tuning and validation. *Journal of Hydrology* **270**: 105–134.

Dregne HE. 1991. Global status of desertification. *Annals of Arid Zone* **30**: 179–185.

Edmunds WM. 2001. Investigation of the unsaturated zone in semi-arid regions using isotopic and chemical methods and applications to water resource problems. In *Isotope Based Assessment of Groundwater Renewal in Water Scarce Regions*, IAEA-Tecdoc-1246, Yurtsever Y (ed.). IAEA: Vienna; 7–22.

Edmunds WM, Gaye CB. 1994. Estimating the variability of groundwater recharge in the Sahel using chloride. *Journal of Hydrology* **156**: 47–59.

Edmunds WM, Tyler SC. 2002. Unsaturated zones as archives of past climates: toward a new proxy for continental regions. *Hydrogeology Journal* **10**: 216–228.

Edmunds WM, Wright EP. 1979. Groundwater recharge and paleoclimate in the Sirte and Kufra Basins, Libya. *Journal of Hydrology* **40**: 215–241.

Edmunds WM, Darling WG, Kinniburgh DG. 1988. Solute profile techniques for recharge estimation in semi-arid and arid terrain. In *Estimation of Natural Groundwater Recharge*, Simmers I (ed.). Reidel Publishing Co: Higham, MA; 139–157.

Edmunds WM, Fellman E, Goni IB. 1999. Lakes, groundwater and palaeohydrology in the Sahel of NE Nigeria: evidence from hydrogeochemistry. *Journal of the Geological Society* **156**: 345–355.

Engel V, Jobbagy EG, Stieglitz M, Williams M, Jackson RB. 2005. Hydrological consequences of eucalyptus afforestation in the argentine pampas. *Water Resources Research* **41**: DOI: 10.1029/2004WR003761.

Favreau G, Leduc C, Schroeter P. 2002a. Discussion–Reply to comment on 'Long-term rise in a Sahelian water-table: the Continental Terminal in South-West Niger' by Leduc, C., Favreau, G., Schroeter, P., 2001. Journal of Hydrology 243, 43–54. *Journal of Hydrology* **255**: 263–265.

Favreau G, Leduc C, Marlin C, Dray M, Taupin JD, Massault M, La Salle CL, Babic M. 2002b. Estimate of recharge of a rising water table in semiarid Niger from H-3 and C-14 modeling. *Ground Water* **40**: 144–151.

Fayer MJ, Gee GW, Rockhold ML, Freshley MD, Walters TB. 1996. Estimating recharge rates for a groundwater model using a GIS. *Journal of Environmental Quality* **25**: 510–518.

Flint AL, Flint LE. 2000. Near surface infiltration monitoring using neutron moisture logging, Yucca Mountain, Nevada. In *Vadose Zone Science and Technology Solutions*, Vol. 1, Looney BB, Falta RW (eds). Columbus, OH, 457–474.

Flint AL, Flint LE. Regional analysis of ground-water recharge. In *Ground-Water Recharge in the Arid and Semiarid Southwest, USA. Part A. Overview and Regional Synthesis*, Stonestrom DA, Leake SA (ed.). US Geological Survey Professional Paper: Reston, VA (in press) .

Flint AL, Flint LE, Hevesi JA, Blainey JB. 2004. Fundamental concepts of recharge in the Desert Southwest: a regional modeling perspective. In *Groundwater Recharge in a Desert Environment: The Southwestern United States*, *Water Science and Applications Series*, Vol. 9, Hogan JF, Phillips FM, Scanlon BR (ed.). American Geophysical Union: Washington, DC; 159–184.

Flint AL, Flint LE, Bodvarsson GS, Kwicklis EM, Fabryka-Martin JT. 2001. Evolution of the conceptual model of vadose zone hydrology for Yucca Mountain. *Journal of Hydrology* **247**: 1–30.

Flint AL, Flint LE, Kwicklis EM, Fabryka-Martin JM, Bodvarsson GS. 2002. Estimating recharge at Yucca Mountain, Nevada, USA: comparison of methods. *Hydrogeology Journal* **10**: 180–204.

Foley JA, Levis S, Costa MH, Cramer W, Pollard D. 2000. Incorporating dynamic vegetation cover within global climate models. *Ecological Applications* **10**: 1620–1632.

Foster S, Garduno H, Evans R, Olson D, Tian Y, Zhang W, Han Z. 2004. Quaternary aquifer of the North China plain—assessing and achieving groundwater resource sustainability. *Hydrogeology Journal* **12**: 81–93.

Gaye CB, Edmunds WM. 1996. Groundwater recharge estimation using chloride, stable isotopes and tritium profiles in the sands of northwestern Senegal. *Environmental Geology* **27**: 246–251.

Gee GW, Wierenga PJ, Andraski BJ, Young MH, Fayer MJ, Rockhold ML. 1994. Variations in water balance and recharge potential at three western desert sites. *Soil Science Society of America Journal* **58**: 63–71.

George RJ, Nulsen RA, Ferdowsian R, Raper GP. 1999. Interactions between trees and groundwaters in recharge and discharge areas–A survey of Western Australian sites. *Agricultural Water Management* **39**: 91–113.

Gieske ASM, Selaolo ET, Beekman HE. 1995. Tracer interpretation of moisture transport in a Kalahari sand profile. In *Application of Tracers in Arid Zone Hydrology*, IAHS Publication 232, Adar EM, Leibundgut C (eds). IAHS: Vienna; 373–382.

Goodrich DC, Williams DG, Unkrich CL, Hogan JF, Scott RL, Hultine KR, Pool D, Coes AL, Miller S. 2004. Comparison of methods to estimate ephemeral channel recharge, Walnut Gulch, San Pedro River Basin, Arizona. In *Groundwater Recharge in a Desert Environment: The Southwestern United States*, *Water Science and Applications Series*, Vol. 9, edited by Hogan JF, Phillips FM, Scanlon BR, American Geophysical Union: Washington, DC; 77–99.

Guendouz A, Moulla AS, Edmunds WM, Zouari K, Shand P, Mamou A. 2003. Hydrogeochemical and isotopic evolution of water in the Complexe Terminal aquifer in the Algerian Sahara. *Hydrogeology Journal* **11**: 483–495.

Halm D, Gaiser T, Stahr K. 2002. Seepage and groundwater recharge in sandy soils of the semi-arid region of Picos, Northeast Brazil. *Neues Jahrbuch Fur Geologie Und Palaontologie-Abhandlungen* **225**: 85–101.

Hanson RT, Newhouse MW, Dettinger MD. 2004. A methodology to assess relations between climatic variability and variations in hydrologic time series in the southwestern United States. *Journal of Hydrology* **287**: 252–269.

Harrington GA, Cook PG, Herczeg AL. 2002. Spatial and temporal variability of ground water recharge in central Australia: A tracer approach. *Ground Water* **40**: 518–527.

Heilweil VM, Solomon DK. 2004. Millimeter- to kilometer-scale variations in vadose-zone bedrock solutes: implications for estimating recharge in arid settings. In *Groundwater Recharge in a Desert Environment: The Southwestern United States*, Hogan JF, Phillips FM, Scanlon BR (eds). American Geophysical Union: Washington, DC; 235–254.

Heilweil VM, Solomon DK, Gardner PM. 2006. Borehole environmental tracers for evaluating net infiltration and recharge through desert bedrock. *Vadose Zone Journal* **5**: 98–120.

Hendrickx J, Walker G. 1997. Recharge from precipitation. In *Recharge of Phreatic Aquifers in (Semi-) Arid Areas*, Simmers I (ed.). A.A. Balkema: Rotterdam, The Netherlands; 19–98.

Herczeg AL, Dogramaci SS, Leaney FWJ. 2001. Origin of dissolved salts in a large, semi-arid groundwater system: Murray Basin, Australia. *Marine and Freshwater Research* **52**: 41–52.

Herczeg AL, Leaney FWJ, Stadter MF, Allan GL, Fifield LK. 1997. Chemical and isotopic indicators of point-source recharge to a karst aquifer, South Australia. *Journal of Hydrology* **192**: 271–299.

Hevesi JA, Flint AL, Flint LE. 2003. Simulation of net infiltration and potential recharge using a distributed-parameter watershed model of the death valley region, Nevada and California. US Geological Survey Water-Resources Investigations Report 03–4090, USGS: Sacramento, USA; 171.

Hogan JF, Phillips FM, Scanlon BR. 2004. *Groundwater Recharge in a Desert Environment: The Southwestern United States: Water Science Applications Series*, Vol. 9. American Geophysical Union: Washington, DC; 294.

Hutton JT. 1976. Chloride in rainwater in relation to distance from ocean. *Search* **7**: 207–208.

IAEA. 2001. *Isotope Based Assessment of Groundwater Renewal in Water Scarce Regions*, IAEA TecDoc 1246. IAEA: Vienna; 273.

Izbicki JA. 2002. Geologic and hydrologic controls on the movement of water through a thick, heterogeneous unsaturated zone underlying an intermittent stream in the western Mojave Desert, southern California. *Water Resources Research* **38**: 1–14.

Jin M, Zhang R, Sun L, Gao Y. 1999. Temporal and spatial soil water management: a case study in the Heilonggang region, PR China. *Agricultural Water Management* **42**: 173–187.

Jin M, Liang X, Simmers I, Gao Y, Zhang R. 2000. *Estimation of Groundwater Recharge Using Artificial Tritium Tracing*. China Environmental Science Press: Wuhan; 340–345.

Jobbagy EG, Jackson RB. 2004. Groundwater use and salinization with grassland afforestation. *Global Change Biology* **10**: 1299–1312.

Kahya E, Dracup JA. 1994. The influences of type 1 El Nino and La Nina events on streamflows in the Pacific Southwest of the United States. *Journal of Climate* **6**: 965–976.

Keese KE, Scanlon BR, Reedy RC. 2005. Assessing controls on diffuse groundwater recharge using unsaturated flow modeling. *Water Resources Research* **41**: W06010, DOI:06010·01029/02004WR003841.

Kendy E, Zhang Y, Liu C, Wang J, Steenhuis T. 2004. Groundwater recharge from irrigated cropland in the North China plain: case study of Luancheng County, Hebei Province, 1949–2000. *Hydrological Processes* **18**: 2289–2302.

Kendy E, Gerard-Marchant P, Walter MT, Zhang Y, Liu C, Steenhuis TS. 2003. A soil-water-balance approach to quantify groundwater recharge from irrigated cropland in the North China Plain. *Hydrological Processes* **17**: 2011–2031.

Kinzelbach W, Aeschbach W, Alberich C, Goni IB, Beyerle U, Brunner P, Chiang W-H, Rueedi J, Zoellman K. 2002. *A Survey of Methods for Groundwater Recharge in Arid and Semi-Arid Regions, Early Warning and Assessment Report Series, UNEP/DEWA/RS.02-2*. United Nations Environment Programme: Nairobi, ISBN 92-80702131-80702133.

Latta J, O'Leary GJ. 2003. Long-term comparison of rotation and fallow tillage systems of wheat in Australia. *Field Crops Research* **83**: 173–190.

Leaney FW, Allison GB. 1986. Carbon-14 and stable isotope data for an area in the Murray Basin: its use in estimating recharge. *Journal of Hydrology* **88**: 129–145.

Leaney FW, Herczeg AL. 1995. Regional recharge to a karst aquifer estimated from chemical and isotopic composition of diffuse and localised recharge. *Journal of Hydrology* **164**: 363–387.

Leduc C, Favreau G, Schroeter P. 2001. Long-term rise in a Sahelian water-table: the continental terminal in south-west Niger. *Journal of Hydrology* **243**: 43–54.

Le Maitre DC, Scott DF, Colvin C. 1999. A review of information on interactions between vegetation and groundwater. *Water Sa* **25**: 137–152.

Lerner DN, Issar AS, Simmers I. 1990. Groundwater recharge, a guide to understanding and estimating natural recharge. International Association of Hydrogeologists, Kenilworth, Rep 8, 345 pp.

Lins HF, Slack JR. 1999. Streamflow trends in the United States. *Geophysical Research Letters* **26**: 227–230.

Liu CM, Xia J. 2004. Water problems and hydrological research in the Yellow River and the Huai and Hai River basins of China. *Hydrological Processes* **18**: 2197–2210.

Love AJ, Herczeg AL, Sampson L, Cresswell RG, Fifield LK. 2000. Sources of chloride and implications for 36Cl dating of old groundwater, southwestern Great Artesian Basin, Australia. *Water Resources Research* **36**: 1561–1574.

Mahlknecht J, Schneider J, Merkel B, de Leon IN, Bernasconi S. 2004. Groundwater recharge in a sedimentary basin in semi-arid Mexico. *Hydrogeology Journal* **12**: 511–530.

Manning AH, Solomon DK. 2004. Constraining mountain-block recharge to the eastern Salt Lake Valley, Utah with dissolved noble gas and tritium data. In *Groundwater Recharge in a Desert Environment: The Southwestern United States*, *Water Science and Applications Series*, Vol. 9, edited by Hogan JF, Phillips FM, Scanlon BR, American Geophysical Union: Washington, DC; 139–158.

Mantua NJ, Hare SR. 2002. The pacific decadal oscillation. *Journal of Oceanography* **58**: 35–44.

McCabe GJ, Dettinger MD. 1999. Decadal variations in the strength of ENSO teleconnections with precipitation in the western United States. *International Journal of Climatology* **19**: 1399–1410.

McFarlane DJ, George RJ. 1992. Factors affecting dryland salinity on two wheatbelt catchments in Western Australia. *Australian Journal of Soil Research* **30**: 85–100.

McMahon PB, Dennehy KF, Ellett KM, Sophocleous MA, Michel RL, Hurlbut DB. 2003. Water movement through thick unsaturated zones overlying the central high plains aquifer, southwestern Kansas, 2000–2001. USGS Water Resources Investigations Report 03–4171, 35.

McMahon PB, Dennehy KF, Bruce BW, Bohlke JK, Michel RL, Gurdak JJ, Hurlbut DB. 2006. Storage and transit time of chemicals in thick unsaturated zones under rangeland and irrigated cropland, High Plains, USA. *Water Resources Research* **42**: DOI: 10.1029/2005WR004417.

Myneni RB, Los SO, Tucker CJ. 1996. Satellite-based identification of linked vegetation index and sea surface temperature anomaly areas from 1982–1990 for Africa, Australia and South America. *Geophysical Research Letters* **23**: 729–732.

Nativ R, Adar E, Dahan O, Geyh M. 1995. Water recharge and solute transport through the vadose zone of fractured chalk under desert conditions. *Water Resources Research* **31**: 253–261.

Navada SV, Nair AR, Sinha UK, Kulkarni UP, Joseph TB. 2001. Application of isotopes and chemistry in unsaturated zone in arid areas of Rajasthan, India. In *Isotope Based Assessment of Groundwater Renewal in Water Scarce Regions*, IAEA-Tecdoc-1246, Yurtsever Y (ed.). IAEA: Vienna; 119–130.

Newman BD, Campbell AR, Wilcox BP. 1997. Tracer-based studies of soil water movement in semi-arid forests of New Mexico. *Journal of Hydrology* **196**: 251–270.

Nimmo JR, Deason JA, Izbicki JA. 2002. Evaluation of unsaturated zone water fluxes in heterogeneous alluvium at a Mojave Basin site. *Water Resources Research* **38**: 1215, DOI:1210·1029/2001WR000735.

O'Connell MG, O'Learey GJ, Connor DJ. 2003. Drainage and change in soil water storage below the root-zone under long fallow and continuous cropping sequences in the Victorian Mallee. *Hydrological Processes* **54**: 663–675.

O'Connor TG. 1985. A synthesis of field experiments concerning the grass layer in the savanna regions of southern Africa. Report No 114. South African National Scientific Programmes, Foundation for Research Development: Pretoria.

Pachur HJ, Kropelin S. 1987. Wadi Howar–Paleoclimatic evidence from an extinct river system in the Southeastern Sahara. *Science* **237**: 298–300.

Phillips FM. 1994. Environmental tracers for water movement in desert soils of the American Southwest. *Soil Science Society of America Journal* **58**: 14–24.

Phillips FM, Mattick JL, Duval TA. 1988. Chlorine 36 and tritium from nuclear weapons fallout as tracers for long-term liquid movement in desert soils. *Water Resources Research* **24**: 1877–1891.

Piechota TC, Chiew FHS, Dracup JA, McMahon TA. 1998. Seasonal streamflow forecasting in eastern Australia and the El Nino Southern oscillation. *Water Resources Research* **34**: 3035–3044.

Pool DR. 2005. Variations in climate and ephemeral channel recharge in southeastern Arizona, United States. *Water Resources Research* **41**(11): W11403. DOI:10·1029/2004WR003255.

Prudic DE. 1994. Estimates of percolation rates and ages of water in unsaturated sediments at two Mojave Desert sites, California-Nevada. US Geological Survey Water Resources Investigations Report 94–4160, 19.

Prych EA. 1998. Using chloride and chlorine-36 as soil-water tracers to estimate deep percolation at selected locations on the US Department of Energy Hanford Site. Water Supply Paper 2481. US Geological Survey: Washington, DC; 67.

Rangarajan R, Athavale RN. 2000. Annual replenishable ground water potential of India–an estimate based on injected tritium studies. *Journal of Hydrology* **234**: 35–83.

Redmond KT, Koch RW. 1991. Surface climate and streamflow variability in the western United States and their relationship to large-scale circulation indices. *Water Resources Research* **27**: 2381–2399.

Roark DM, Healy DF. 1998. Quantification of deep percolation from two flood-irrigated alfalfa fields, Roswell Basin, New Mexico. USGS Water Resources Investigations Report 98–4096, 32.

Ropelewski CF, Halpert MS. 1987. Global and regional precipitation patterns associated with El-Nino Southern Oscillation. *Monthly Weather Review* **115**: 1606–1626.

Ruifen L, Keqin W. 2001. Environmental isotope profiles of the soil water in loess unsaturated zone in semi-arid areas of China. In *Isotope Based Assessment of Groundwater Renewal in Water Scarce Regions*, IAEA Tecdoc-1246, Yurtsever Y (ed.). IAEA: Vienna, 101–118.

Sadras VO, Roget DK. 2004. Production and environmental aspects of cropping intensification in a semiarid environment of southeastern Australia. *Agronomy Journal* **96**: 236–246.

Salama R, Hatton T, Dawes WR. 1999. Predicting land use impacts on regional scale groundwater recharge and discharge. *Journal of Environmental Quality* **28**: 446–460.

Salama R, Farrington P, Bartle G, Watson G. 1993. Salinity trends in the wheatbelt of Western Australia: results of water and salt balance studies from Cuballing catchment. *Journal of Hydrology* **145**: 41–63.

Sami K, Hughes DA. 1996. A comparison of recharge estimates to a fractured sedimentary aquifer in South Africa from a chloride mass balance and an integrated surface-subsurface model. *Journal of Hydrology* **179**: 111–136.

Sanford WE, Wood WW. 2001. Hydrology of the coastal sabkhas of Abu Dhabi, United Arab Emirates. *Hydrogeology Journal* **9**: 358–366.

Sanford WE, Plummer LN, McAda DP, Bexfield LM, Anderholm SK. 2004. Hydrochemical tracers in the Middle Rio Grande Basin, USA: 2. Calibration of a ground-water flow model. *Hydrogeology Journal* **12**: 389–407.

Scanlon BR. 1991. Evaluation of moisture flux from chloride data in desert soils. *Journal of Hydrology* **128**: 137–156.

Scanlon BR. 1992. Evaluation of liquid and vapor flow in desert soils based on chlorine-36 and tritium tracers and nonisothermal flow simulations. *Water Resources Research* **28**: 285–297.

Scanlon BR. 1996. Unsaturated-zone characterization for low-level radioactive waste disposal in Texas. *Geotimes* **41**: 22–25.

Scanlon BR. 2000. Uncertainties in estimating water fluxes and residence times using environmental tracers in an arid unsaturated zone. *Water Resources Research* **36**: 395–409.

Scanlon BR, Cook PG. 2002. Preface: Theme issue on groundwater recharge. *Hydrogeology Journal* **10**: 3–4.

Scanlon BR, Goldsmith RS. 1997. Field study of spatial variability in unsaturated flow beneath and adjacent to playas. *Water Resources Research* **33**: 2239–2252.

Scanlon BR, Langford RP, Goldsmith RS. 1999. Relationship between geomorphic settings and unsaturated flow in an arid setting. *Water Resources Research* **35**: 983–999.

Scanlon BR, Goldsmith RS, Langford RP. 2000. Relationship between arid geomorphic settings and unsaturated zone flow: case study, Chihuahuan Desert, Texas. Bureau of Economic Geology Report of Investigations No. 261. University Texas Austin: Austin, TX; 133.

Scanlon BR, Healy RW, Cook PG. 2002. Choosing appropriate techniques for quantifying groundwater recharge. *Hydrogeology Journal* **10**: 18–39.

Scanlon BR, Keese K, Reedy RC, Simunek J, Andraski BJ. 2003. Variations in flow and transport in thick desert vadose zones in response to paleoclimatic forcing (0–90 kyr): field measurements, modeling, and uncertainties. *Water Resources Research* **39**: 1179, DOI:1110·1029/2002WR001604.

Scanlon BR, Levitt DG, Keese KE, Reedy RC, Sully MJ. 2005a. Ecological controls on water-cycle response to climate variability in deserts. *Proceedings of the National Academy of Sciences of the United States of America* **102**: 6033–6038.
Scanlon BR, Reedy RC, Stonestrom DA, Prudic DE, Dennehy KF. 2005b. Impact of land use and land cover change on groundwater recharge and quality in the southwestern USA. *Global Change Biology* **11**: 1577–1593.
Selaolo ET. 1998. Tracer studies and groundwater recharge assessment in the eastern fringe of the Botswana Kalahari–The Letlhakeng-Botlhapatlou area. Ph.D. Thesis, Free University, Amsterdam, 229.
Selaolo ET, Beekman HE, Gieske ASM, de Vries JJ. 1996. Multiple tracer profiling in Botswana–GRES findings. In *Groundwater Recharge Estimation in Southern Africa*, *UNESCO IHP Series No. 64*, Xu Y, Beekman HE (ed.). UNESCO: Paris; 33–50.
Sharma ML. 1989. *Groundwater Recharge*. A.A. Balkema: Rotterdam, 323.
Simmers I. 1988. *Estimation of Natural Groundwater Recharge*. D. Reidel Publishing Co: Boston, MA; 510.
Simpson HJ, Cane MA, Herczeg AL, Zebiak SE, Simpson JH. 1993. Annual river discharge in southeastern Australia related to El-Nino Southern oscillation forecasts of sea-surface temperatures. *Water Resources Research* **29**: 3671–3680.
Smiles DE, Gardner WR, Shulz RK. 1995. Diffusion of tritium in arid disposal sites. *Water Resources Research* **31**: 1483–1488.
Sophocleous M. 1992. Groundwater recharge estimation and regionalization: the Great Bend Prairie of central Kansas and its recharge statistics. *Journal of Hydrology* **137**: 113–140.
Stephens DB, Knowlton RJ. 1986. Soil water movement and recharge through sand at a semiarid site in New Mexico. *Water Resources Research* **22**: 881–889.
Stonestrom DA, Leake SA. Ground-water recharge in the arid and semiarid southwest, USA. *US Geological Survey Professional Paper*. US Geological Survey: Reston, VA (in press).
Stonestrom DA, Prudic DE, Laczniak RJ, Akstin KC. 2004. Tectonic, climatic, and land-use controls on groundwater recharge in an arid alluvial basin: Amargosa Desert, USA. In *Groundwater Recharge in a Desert Environment: The Southwestern United States*, *Water Science and Applications Series*, Vol. 9, American Geophysical Union: Washington, DC, 29–47.
Subyani AM. 2004. Use of chloride-mass balance and environmental isotopes for evaluation of groundwater recharge in the alluvial aquifer, Wadi Tharad, western Saudi Arabia. *Environmental Geology* **46**: 741–749.
Subyani AM. 2005. Hydrochemical identification and salinity problem of ground-water in Wadi Yalamlam basin, Western Saudi Arabia. *Journal of Arid Environments* **60**: 53–66.
Sukhija BS, Reddy DV, Nagabhushanam P, Hussain S. 2003. Recharge processes: piston flow vs preferential flow in semi-arid aquifers of India. *Hydrogeology Journal* **11**: 387–395.
Szilagyi J, Harvey FE, Ayers JF. 2005. Regional estimation of total recharge to ground water in Nebraska. *Ground Water* **43**: 63–69.
Tyler SW, Chapman JB, Conrad SH, Hammermeister DP, Blout DO, Miller JJ, Sully MJ, Ginanni JM. 1996. Soil-water flux in the southern Great Basin, United States: temporal and spatial variations over the last 120,000 years. *Water Resources Research* **32**: 1481–1499.
Tyler SW, McKay WA, Mihevc TM. 1992. Assessment of soil moisture movement in nuclear subsidence craters. *Journal of Hydrology* **139**: 159–181.
UNESCO. 1979. Map of the world distribution of arid regions. Man and Biosphere Tech Notes, no. 7, UNESCO: Paris; 54.
US Census Bureau. 2004. Global Population Profile: 2002. International Population Reports WP/02. US Government Printing Office: Washington, DC.
van der Kamp G, Hayashi M, Gallen D. 2003. Comparing the hydrology of grassed and cultivated catchments in the semi-arid Canadian prairies. *Hydrological Processes* **17**: 559–575.
Venencio MV. 2002. Climate variability and ground water resources. *Sixth International Conference on Southern Hemisphere Meteorology and Oceanog*, Long Beach, CA, Feb. 2002, 142–144.
Vogelmann JE, Howard SM, Yang L, Larson CR, Wylie BK, van Driel N. 2001. Completion of the 1990s national land cover data set for the conterminous United States from Landsat Thematic Mapper data and ancillary data sources. *Photogrammetric Engineering and Remote Sensing* **67**: 650–662.
Walker GR, Jolly ID, Cook PG. 1991. A new chloride leaching approach to the estimation of diffuse recharge following a change in land use. *Journal of Hydrology* **128**: 49–67.
Walvoord MA, Plummer MA, Phillips FM, Wolfsberg AV. 2002. Deep arid system hydrodynamics, 1, Equilibrium states and response times in thick desert vadose zones. *Water Resources Research* **38**: 1308, DOI: 1310.1029/2001WR000824.
Wang XP, Berndtsson R, Li XR, Kang ES. 2004a. Water balance change for a re-vegetated xerophyte shrub area. *Hydrological Sciences Journal-Journal Des Sciences Hydrologiques* **49**: 283–295.
Wang XP, Brown-Mitic CM, Kang ES, Zhang JG, Li XR. 2004b. Evapotranspiration of Caragana korshinskii communities in a revegetated desert area: Tengger Desert, China. *Hydrological Processes* **18**: 3293–3303.
WHO. 2003. *Right to Water*. *Health and Human Rights Publication Series No. 3*, World Health Organization: Geneva, Switzerland; 44.
Wilson JL, Guan H. 2004. Mountain block hydrology and mountain front recharge. In *Groundwater Recharge in a Desert Environment: The Southwestern United States*, *Water Science and Applications Series*, Vol. 9, edited by Hogan JF, Phillips FM, Scanlon BR. American Geophysical Union: Washington, DC; 113–137.
Wood WW, Sanford WE. 1995. Chemical and isotopic methods for quantifying ground-water recharge in a regional, semiarid environment. *Ground Water* **33**: 458–468.
Zhang L, Walker GR (eds). 1998. *The Basics of Recharge and Discharge*, CSIRO Publishing: Collingwood.
Zhang L, Dawes WR, Hatton TJ, Reece PH, Beale GTH, Packer I. 1999. Estimation of soil moisture and groundwater recharge using the TOPOG_IRM model. *Water Resources Research* **35**: 149–161.
Zhu C. 2000. Estimate of recharge from radiocarbon dating of groundwater and numerical flow and transport modeling. *Water Resources Research* **36**: 2607–2620.