International Association of Hydrogeologists

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Groundwater Recharge

A Guide to Understanding and Estimating Natural Recharge

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International Contributions to Hydrogeology
Founded by
G. Castany, E. Groba, E. Romijn

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PREFACE

At its Sixth Session in Paris, 22-30 March 1984, the Intergovernmental Council of the International Hydrological Programme (IHP) approved the activities to be undertaken during Phase III of the IHP (1984-1989). The overall title of Phase III is 'Hydrology and the scientific bases for the rational management of water resources for economic and social development'. The plan is broadly based, having regard to the varying needs of the developed and developing countries and the fact that the execution of IHP activities in Member States is and will be based on their specific social, economic and cultural patterns.

The plan of Phase III identifies eighteen themes which have been grouped under four main sections. Section I deals with hydrological processes and parameters for water projects, and includes Theme 2.4 'Use of physical and mathematical models for studying the regime of groundwater and predicting changes in quantity and quality'. Project 2.4b produced a short document published in 1987 by Unesco on 'The value of groundwater models for planners and decision makers'. In the framework of Project 2.4c two activities were planned: to hold an international workshop on 'Estimation of natural groundwater recharge' and to prepare and publish a manual of practice on the same subject. Project 2.4d discusses the key issues in groundwater modelling, the representativeness of data and the spatial variability of hydrological variables and parameters. The report 'Consequences of spatial variability in aquifer properties and data limitations for groundwater modelling practice' was published as the International Association of Hydrological Sciences publication no. 175 during 1988.

In 1984 Unesco invited the International Association of Hydrogeologists (IAH) to contribute in two ways to project 2.4c. of its ongoing International Hydrological Programme; viz,

- to hold an international workshop on 'Estimation of Natural Groundwater Recharge'; and
- to prepare and publish a manual of practice on the same subject.

IAH accepted the invitation and in 1985 established a working group under the leadership of Ian Simmers (Amsterdam Free University), with as active members Okay Eroskay (Turkey), Arie Issar (Israel), Gert Knutsson (Sweden), David Lerner (UK) and Erik Romijn (The Netherlands).

From an early stage it was decided by the working group that the target for both activities would be the world's arid and semi-arid zones, these being the areas where the need for reliable estimates of groundwater recharge are greatest. African arid zones in particular have experienced severe droughts during the last decade, causing considerable water supply difficulties, while in a broader (semi-)arid zone framework overexploitation of natural resources, including groundwater, and rapid urban development have created major socio-economic problems.

The international workshop, held in Antalya, Turkey, from 8 to 15 March 1987, was attended by 42 participants from 17 countries and a number of invited observers. Principal organisers were the IAH and Amsterdam Free University (Department of Hydrogeology), with cooperation/support from the University of Istanbul (Engineering Geology section), the State Hydraulic Works of Turkey (DSI), IAEA and IAHS. The workshop was sponsored by NATO Scientific Affairs Division, the US Army European Research Office and Unesco. The Netherlands Ministry of Foreign Affairs provided support funding for several participants from developing countries. Proceedings of the meeting have since been published by Reidel in the NATO ASI-Series C as vol. 222 (1988).

The present 'manual of practice' reflects working group opinions and concerns with respect to the state-of-the-art of arid/semi-arid area groundwater recharge estimation. The volume is not intended as a 'cookbook', but offers guidance to the practitioner engaged in arid and semi-arid zone water resources exploration and development. The volume is in four parts:

Part I introduces the study framework, defines the recharge concepts which follow, and discusses the problems of space and time variability in relation to the translation of point measurements to regional recharge estimates. Brief comments are also given on some of the implications for resource management.

Part II deals with the concept of hydrogeological provinces. Characteristics and case studies are summarized and discussed for each, thus developing a series of typical hydrogeological conceptual models, the section ending with a general procedure algorithm for deriving 'first estimate' recharge values.

Part III gives details and examples of techniques currently available for quantifying groundwater recharge. Specifically considered are direct measurements, water balance and soil moisture budgetting methods, Darcian approaches, tracer techniques and empirical procedures. Each is comprehensively and critically evaluated with respect to recharge source (precipitation, rivers, interaquifer flows, irrigation and urbanisation), with summaries for ready reference.

Part IV closes the volume with a series of case studies chosen to illustrate the use of various techniques in a number of hydrogeological provinces. Since the examples given are largely abridged versions of papers already contained in the Antalya workshop proceedings, the authors and working group acknowledge the willing cooperation of the publishers (D. Reidel, Dordrecht) in making the material available.

Numerous individuals and organisations have been involved either directly or indirectly in the preparation of this manual. Financial support was provided by Unesco, the Swedish IHP National Committee and in fellowship form to one of the authors by the Jacob Blaustein Institute for Desert Research (Ben-Gurion University of the Negev, Israel). Also gratefully acknowledged are the personal contributions from Ron Passchier (Part II), Dr. S.D. Limaye (Part II, volcanic terrains), Robert Gray (Part III) and Ersin Seyhan. Per-Olof Johansson (Sweden) served as technical editor for the volume and valuable review advice was received from Dr. D.C.H. Senarath (University of Moratuwa, Sri Lanka), Dr. E.S. Simpson (University of Arizona, USA) and the Hydrological Branch of IAEA. Mr. Nelson da Franca, Programme Specialist of the Division of Water Sciences of Unesco, was the responsible person within the IHP Secretariat for this project. The manual would not have been possible without these various forms of support and the considerable team effort by an active working group.

My personal appreciation, as Chairman, goes also to the IAH Council, to the principal authors, and in particular to Erik Romijn for his dedication to scientific and administrative detail.

Ian Simmers
Chairman,
Working Group on Estimation of Natural Groundwater Recharge

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GROUNDWATER RECHARGE

A guide to understanding and estimating natural recharge

Part I : ARIDITY, GROUNDWATER RECHARGE AND WATER RESOURCES MANAGEMENT

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1 ARIDITY, GROUNDWATER RECHARGE AND WATER RESOURCES MANAGEMENT

In this volume on natural and 'man-induced' groundwater recharge estimation the principal concern is with how best to quantify and hence model the process, with a view to providing a more rational approach to overall water resource management. Target areas for the discussions and outlines of the numerous available procedures which follow are the world's arid and semi-arid zones.

It must be stressed at the outset that the information contained represents an appraisal of the present state-of-the-art with respect to arid/semi-arid area recharge determination and does not aspire to being the ultimate word on the subject. Standard procedures for the collection and processing under arid or semi-arid conditions of such hydrological variables as precipitation, evapotranspiration and streamflow are not described in detail; for these reference should be made to one of the various text- or handbooks (e.g. FAO, 1981). Finally, the volume is not intended as a 'cookbook' on the general problems of recharge estimation. It does not, therefore relieve the reader of the need for independent thought on a specific problem, but should be considered as a source of information to facilitate a logical and structured approach to the steps involved.

Initial motivation for this manual of practice is that one third of the world's land surface has been classified as arid or semi-arid and approximately half the countries are directly affected in some way by problems of aridity (UNESCO, 1977, 1979). Easily developed land has in large measure already been exploited and attention is thus increasingly towards more arid areas for human survival. However, soil and water resources of arid and semi-arid regions are limited, often being in a delicate environmental balance. Surface water supplies are normally critically unreliable, poorly distributed and subject to high evaporation losses. For the rapidly expanding urban, industrial and agricultural water requirements in these areas, groundwater use is thus of fundamental importance. This in turn creates a host of associated problems since, for example, abundant available groundwater may have only small natural recharge, thus raising such issues as mining a non-renewable resource, quality deterioration by saline water intrusion and land subsidence.

Quantification of the current rate of natural groundwater recharge is thus a basic prerequisite for efficient groundwater resource management, and is particularly vital in arid regions where such resources are often the key to economic development (Foster, 1988). Unfortunately, of all the factors in the evaluation of groundwater resources, this rate of aquifer replenishment is one of the most difficult to derive. Equally true is that it usually takes time for social awareness of a new problem to be aroused and effective controls initiated. By this time groundwater may be exhausted and large capital investments lost. It may therefore be concluded (FAO, 1981) that 'a higher level of competence, not only technical but social and political, is needed in arid than in humid zones to achieve sustained progress'.

These above factors serve to illustrate the growing international demand for reliable quantitative information on arid and semi-arid zone groundwater recharge estimation and hence form the catalyst for the present manual.

1.1 Definitions

1.1.1 Aridity

Although terms such as aridity are somewhat vague, with any classification influenced by the intended use, a number of environmental features characterise the so-called arid and semi-arid areas of the earth (FAO, 1981):

- 'high levels of incident solar radiation;
- generally high diurnal and seasonal temperature variations;
- low humidity at short distance from the sea;
- strong winds with frequent dust and sand storms;
- sporadic rainfall of high temporal and spatial variability;
- extreme variability of short-duration runoff events in ephemeral drainage systems;
- generally high infiltration rates in channel alluvium;
- high sediment transport rates;
- relatively large groundwater and soil moisture storage changes;
- distinctive geomorphology, with negligible weathering processes and poorly developed soil profiles'.

The essential characteristic, however, and the one upon which all others depend, is the smallness of precipitation.

Principal factors causing aridity, either singly or in combination, are summarised by UNESCO (1977) and Lloyd (1986) as:

- the high pressure belts located at sub-tropical latitudes, giving hot, dry subsiding air;
- continentality and coastal mountain rain-shadow effects;
- the effects of cold oceanic currents along some coasts.

All these factors are evident in the readily available maps of arid and semi-arid areas presented by UNESCO (1953, 1958, 1979) and as shown in simplified form by Fig. 1.1 taken from Hodge and Duisberg (1963).

Precise definitions of aridity remain difficult, despite the many attempts found in the literature, because of the variety of climatic and other data (e.g., topography, soil condition, history and type of landuse) which must be taken into account.

A selection of these based solely on annual average precipitation (mm) is as follows:

Hyperarid	Arid	Semi-arid	Reference
0-50	50-200	200-500	Lloyd (1986)
-	< 100	100-500	G. Droughin (UNESCO, 1953)
0-200	200-400	400-800	Y.M. Simaika (UNESCO, 1953)

The diversity of these values indicates that total precipitation is not a sufficient definition and that such aspects as rainfall duration, length and timing of the dry season and some measure of temperature or water availability for plant growth also need to be considered for the present manual.

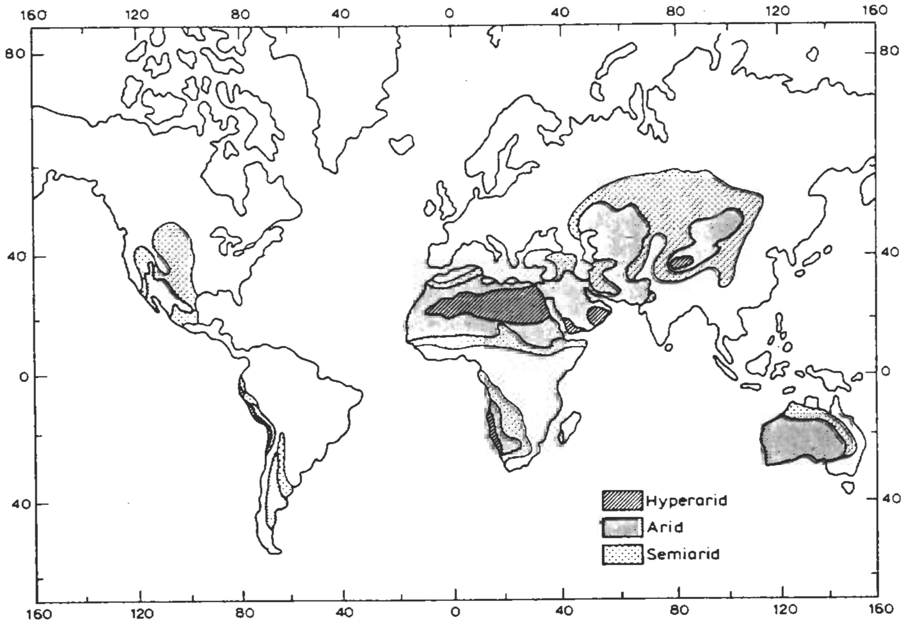

Fig. 1.1 Arid and semi-arid areas of the world (Hodge and Duisberg, 1963)

Failing a more comprehensive classification therefore, that presented by UNESCO (1979), based on the earlier work of Meigs (1953), is preferred for general use. In this, the delimitation of hyperarid, arid and semi-arid areas is based on aridity indices and all available data on soils, relief and vegetation. Full details are given in the UNESCO maps and accompanying explanatory notes, a brief definition of each being:

Hyperarid zone ($p/et_p < 0.03$, where p and et_p are respectively mean annual precipitation and potential evapotranspiration), annual rainfall is very low with interannual variability up to 100%, very sparse vegetation and no rainfed agriculture or grazing.

Arid zone ($0.03 < p/et_p < 0.20$), annual rainfall is 80-150 mm and 200-350 mm in respectively winter and summer rainfall areas, interannual rainfall variability 50-100%, scattered vegetation, nomadic livestock rearing is possible and agriculture based upon local rainfall is only possible through rainwater harvesting techniques.

Semi-arid zone ($0.20 < p/et_p < 0.50$), annual rainfall is 200-500 mm and 300-800 mm in winter and summer rainfall areas, interannual variability 25-50%, discontinuous vegetation with perennial grasses, rainfed agriculture and sedentary livestock rearing are common.

1.1.2 Groundwater recharge

Groundwater recharge may be defined in a general sense as the downward flow of water reaching the water table, forming an addition to the groundwater reservoir. A clear distinction should thus be made, both conceptually and for any modelling purposes, between the potential amount of water available for recharge from the soil zone and the actual recharge as defined above. Rushton (1988) shows that the two quantities may differ, due to either the influence of the unsaturated zone or non-acceptance by the aquifer of the potential value. This aspect is discussed further in Section 11.1.2.

Recharge of groundwater may occur naturally from precipitation, rivers, canals and lakes and as a man-induced phenomenon via such activities as irrigation and urbanisation - losses from irrigation programmes frequently provide a contribution which exceeds that from rainfall.

Two principal types of recharge are recognised, categorised here (Fig. 1.2) as direct and indirect (FAO, 1981; Lloyd, 1986). Other terms which have been used as equivalents are local (or diffuse) and localised recharge (see, for example, Allison, 1988; Foster, 1988).

Direct recharge is defined as water added to the groundwater reservoir in excess of soil moisture deficits and evapotranspiration, by direct vertical percolation of precipitation through the unsaturated zone.

Indirect recharge results from percolation to the water table following runoff and localisation in joints, as ponding in low-lying areas and lakes, or through the beds of surface watercourses. Two distinct categories of indirect recharge are thus evident; viz, that associated with surface water courses, and a second localised form resulting from horizontal surface concentration of water in the absence of well-defined channels (see also sections 11.1.1, 11.8 and Chapter 12).

These definitions are of course a simplification of reality, since lateral subsurface recharge is not explicitly considered, so-called preferred pathways are a common phenomenon with even direct recharge (Sharma and Hughes, 1985;

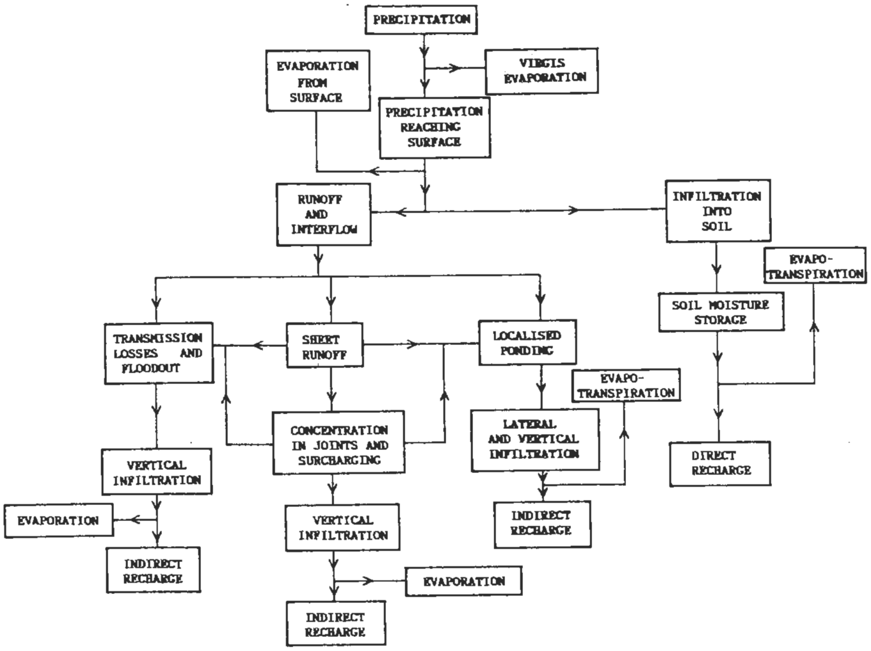

Fig. 1.2 The various elements of recharge in an arid area (Lloyd, 1986)

Johnston, 1987) and in many locations a combination of both direct and indirect recharge, as defined, will occur. However, for modelling purposes a number of general guidelines are evident from the international literature:

- there is no doubt that recharge occurs to some extent in even the most arid regions, though increasing aridity will be characterised by a decreasing net downward flux and greater time variability;

- as aridity increases, direct recharge is likely to become less important and indirect recharge more important in terms of total recharge to an aquifer;

- estimates of direct recharge are likely to be more reliable than those of indirect recharge.

These generalisations indicate that successful groundwater recharge estimation depends on first identifying the probable flow mechanisms and important features influencing recharge for a given locality, since it cannot be assumed that a procedure successfully developed for one area will prove equally reliable for another.

Rushton (1988) lists several of the factors affecting recharge as follows:

At the land surface:

topography
precipitation: magnitude, intensity, duration, spatial distribution
runoff, ponding of water
cropping pattern, actual evapotranspiration

Irrigation:

nature of irrigation scheduling
losses from canals and water courses
application to fields, land preparation, losses from fields

Rivers:

rivers flowing into the study area
rivers leaving the study area
rivers gaining water from or losing water to the aquifer

Soil zone:

nature of the soil, depth, hydraulic properties
variability of the soil, spatially and with depth
rooting depth in soil
cracking of soil on drying out or swelling due to wetting

Unsaturated zone between soil and aquifer:

flow mechanism through unsaturated zone
zones with different hydraulic conductivities

Aquifer:

ability of the aquifer to accept water
variation of aquifer condition with time.

The actual frequency of recharge events and the transit time until recharge takes place are also important, differences obviously influencing both the choice of method for recharge estimation and eventual resource management. For example, infrequent major recharge is a totally different proposition from smaller but more regular events (Fig. 1.3), since in the former case the negative side-effects of overdevelopment may have already occurred prior to the replenishment (Foster, 1988). Further, the existence of extensive well-established aquifer hydraulic gradients is no guarantee of recent recharge. Such features may largely represent paleo-recharge (fossil gradients), with natural recession of groundwater continuing to the present day (De Vries, 1983; Lloyd, 1986).

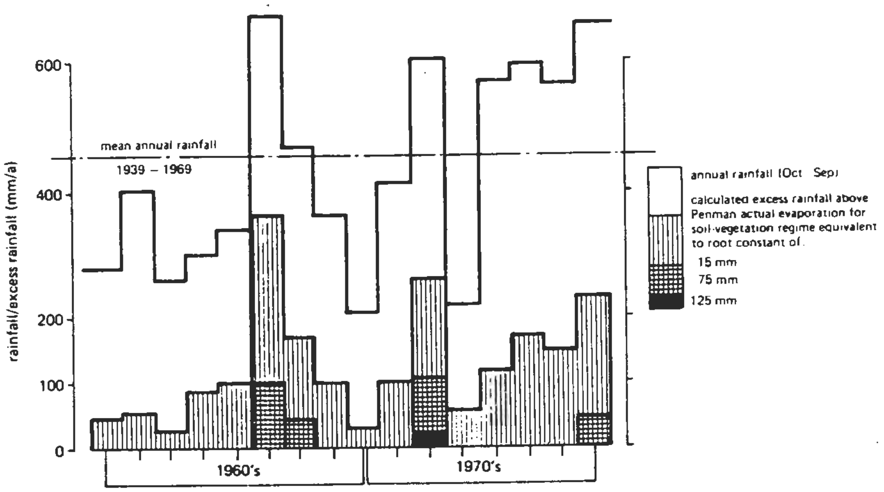

Fig. 1.3 ***Summary*** *of analysis of daily meteorological data for a site in the Botswana Kalahari (Kweneng District) during 1961-77 (Foster, 1988)*

Note: Infiltration rates and frequencies exhibit marked sensitivity to variation in soil moisture-vegetation regime which is in practice laterally variable and difficult to quantify, but groundwater table fluctuations suggest that widespread recharge was limited to a single rainfall episode in the 1971-72 wet season.

1.2 Groundwater recharge processes

Lloyd (1986) suggests that 'hydrological processes in arid areas are no different from those under other climatic regimes, except that in some circumstances the interrelationships between processes are more accentuated under arid conditions and the amounts involved in a process frequently more extreme'. Given a vegetated area this is certainly true for the processes of groundwater recharge, as shown in a relatively simplistic manner by Fig. 1.2. However, a major difficulty in arid areas, thus prompting the present manual, is that although basic recharge mechanisms are reasonably well known, deficiencies are evident in quantifying the various elements. Considering the general scarcity and variability of hydrogeological data in most arid and semi-arid zones, this is to be expected.

It is clear from Section 1.1.2 that differences in sources and processes of groundwater recharge will mean that the applicability of available estimation techniques will also vary. To proceed from a well-defined conceptualisation of the various recharge processes is thus essential.

Although direct recharge is known to be of decreasing significance with increasing aridity, the processes involved are conceptually the easiest to define and form the basis of numerous recharge estimation techniques currently in common use (see Chapter 11). Assuming a dominant vertical moisture flux, a single porous medium and a water table which is not close to the surface, water is postulated to move by Darcian flow in the unsaturated zone to the groundwater body. Since both upward and downward fluxes can occur, for recharge estimation purposes interest lies in the actual steady-state net moisture transfer to the water table. Flow equations representing this net process are not given here and reference should be made to either Section 11.5, Rushton (1988), Johansson (1988), or one of the numerous standard texts on soil physics (e.g., Hillel, 1982).

However, field experiments show that volumetric water content and flow mechanisms in the unsaturated zone vary in a complex manner, the main problem being that the parameters moisture content, matric potential and hydraulic conductivity are sensitively interrelated. For example, a change in the volumetric water content of 5% often corresponds to a change in the hydraulic conductivity by two or more orders of magnitude (Rushton, 1988). Further, material in the unsaturated zone rarely displays homogeneous properties, often consisting of layered sands, silts and clays with widely varying saturated hydraulic conductivities (Fig. 12.2), and a strong potential for lateral rather than vertical flow above lithological discontinuities. The irregular occurrence of preferred pathways in even relatively homogeneous material is an added complication for recharge estimation, as are the problems arising from shallow water tables and from process space and time variability common to arid and semi-arid areas. This last aspect is dealt with further in Section 1.3.

The theoretically simple processes of direct groundwater recharge are thus by no means easy to quantify in nature, and unfortunately the task is even more difficult for either category of indirect recharge. Using Fig. 1.2 as an indicator of indirect recharge mechanisms, Lloyd (1986) concludes that:

- 'the balances between runoff to joints, hydraulic surcharging of materials in joints and evaporative losses coupled with slope, ground surface conditions and erratic precipitation, pose (considerable) problems for hydrological analysis;

- indirect recharge through depression ponding is equally difficult to evaluate as accumulations of clay restrict vertical infiltration while lateral infiltration into adjacent materials is only active with initial flooding;

- transmission losses during flooding are also difficult to quantify. Flood volume differences between two gauging stations are often of the order of measurement error, while any infiltration is subject to high evaporation losses that are impossible to determine'.

In summary, quantification of groundwater recharge is fraught with problems of varying magnitude and hence substantial uncertainties. To reduce result uncertainty it is therefore desirable to apply and compare a number of independent approaches, as allowed by available data.

1.3 Recharge time and space variability

Variations in groundwater recharge with time and in space (both laterally and vertically) are well documented and are the direct consequence of such factors as differing precipitation, soil characteristics, vegetation, landuse and topography.

Given this variability, the obviously interrelated question is what techniques should best be used to derive reliable recharge estimates? Although aspects of this issue are addressed in detail by subsequent chapters, it is clear from the literature that not all methods are strictly comparable in terms of their applicable space and time scales. Some are intended to estimate recharge over an area for long time periods, while others are concerned with short time interval point information.

Table 1.1 Factors influencing the choice of time step for recharge estimation (Lerner, 1987, pers.comm.)

•Time period over which recharge is averaged:	Instantaneous	Event	Season	Year	Historical average	Geological time
•Time steps used for:						
-Scientific studies:	|———	———	———	———	———	———|
-Groundwater resource studies:		|———	———	———	———|	
•Time steps for various factors in a resource study:						
-size of study area:		|← small	———	———	large →|	
-level of study:		|← design	———	———	reconnaissance →|	
-degree of aridity:		|← arid	———	———	humid →|	
-resource exploitation:		|← heavy	———	———	light →|	
-quantity of data:		|← large	———	———	small →|	

Factors which influence the choice of time scale are shown in Table 1.1 - the study objective is clearly of prime importance. From an operational point of view, Table 1.1 should be viewed in conjunction with Fig. 10.1, which shows that although a particular recharge estimation method may be applicable over a spectrum of time scales, some intervals are more directly appropriate than others. This aspect can be quite critical when interest lies in areas with erratic or clustered rainfall, potentially low values of recharge and limited aquifer storage.

1.3.1 Extrapolation in time

Arid and semi-arid zone precipitation is characterised by high interannual variability (Section 1.1.1), as illustrated by Fig. 1.4, resulting in very variable processes over a long time scale. This in turn can lead to considerable recharge estimation problems if long-term values are required with only short-period data available, particularly in the situation of high and/or increasing groundwater exploitation.

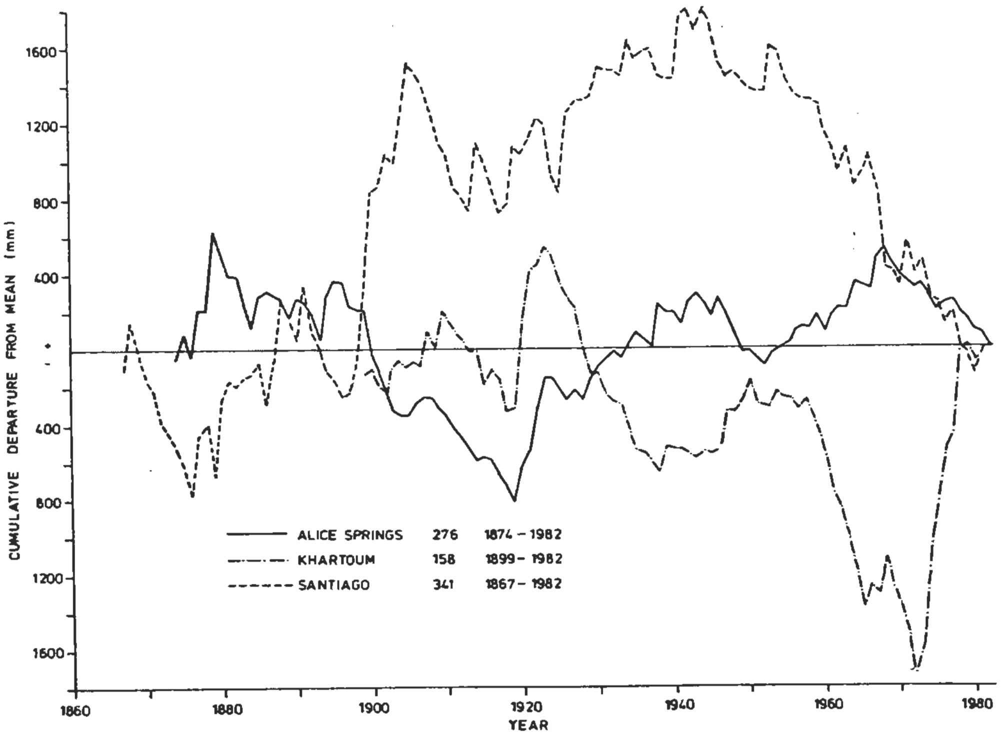

Fig. 1.4 Precipitation trends as cumulative deviations from the mean for example stations in or adjacent to major arid areas. Period mean annual values (mm) shown (Lloyd, 1986)

A possible solution to the problem is to model recharge using stochastically generated long-term rainfall sequences as basic input. For appropriate techniques the reader is referred to Kelman (1977), Beven (1986, 1987) and any of the readily available texts on stochastic modelling.

Although recharge estimation procedures generally assume precipitation and evapotranspiration to be the only time-variant factors affecting the various processes, most techniques can accommodate changes in landuse over the duration of data collection provided recharge response time lies within the period of records. However, if interest is in predicting the consequences for recharge of landuse modifications over time, and hence changes in both vegetation and soil hydraulic characteristics, then a new dimension of complexity is introduced. The obviously related problem is the situation where transit time until recharge is long and landuse changes are known to have occurred in an area prior to current data collection programmes (see also Section 1.4).

Reliable answers to these common management problems are not easily obtained, since the hydrological system is in a state of dynamic evolution, with individual elements of the system characteristically displaying different time frames of adjustment. Current research (e.g., Peck and Williamson, 1987) indicates that the most realistic approach to a solution involves a combination of intensive data collection, translation of nearby or other relevant supporting information and modelling. Unfortunately, rigorous adherence to such an approach, in an attempt to minimise result uncertainty, can be both time consuming and expensive. Some relaxation of pre-modelling data collection is of course always possible, but will in general lead to greater (and perhaps unacceptable) estimation errors.

1.3.2 Spatial extrapolation

As concluded by Allison (1988), probably the most important problem to be overcome in the estimation of groundwater recharge is the assessment and prediction of its spatial variability. Over some quite large areas it appears to show little lateral variability, while in other, apparently similar areas it can range over at least an order of magnitude - numerous examples of this phenomenon are described in Peck and Williamson (1987).

Fig. 1.5 is typical, and shows four profiles of chloride concentration in soil water from what appears to be a uniform field with sand/sandy loam surface soils. Allison (1988) believes that the large variations in chloride concentration reflect correspondingly large changes in recharge rate, the difficulty being that in other apparently similar sites chloride profiles are uniform.

Whatever the reason for the displayed variability, its field identification, quantification and development of statistical or other techniques for estimating recharge over an extended area remain a problem.

This issue has considerable practical importance. If, for example, recharge estimation is based on point measurements, then water resource managers will need to know how or whether these relate to values over a specified area of interest. Unfortunately the cost of multiple point recharge measurements is usually prohibitive, particularly if interannual recharge variability is also high and values are required over an extended time period. A descriptive insight into recharge spatial variability is of course available by way of standard hydrogeological mapping techniques (e.g., borehole logs and pumping tests, hydrochemical sampling, geophysical survey, aerial photograph and thematic map interpretation). However, to create such a map is time consuming and the end product can at best only indicate the general pattern of likely recharge areas and groundwater flow lines. The quantitative information ultimately required for modelling and resource management is not produced by this approach.

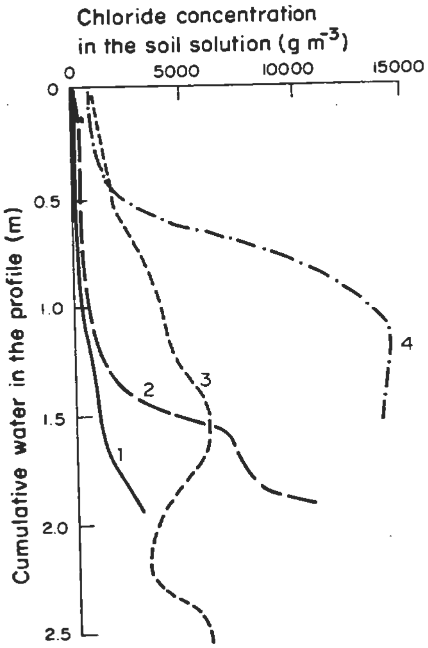

Fig. 1.5 The relationship between chloride concentration of soil water and cumulative water stored in the profile in a field, cleared about 50 years ago, under a pasture-crop rotation (Allison, 1988). All sites are within a radius of 100 m. Rainfall is ≈ 300 mm/a

Strategies to cope with reliable quantitative estimation and prediction of spatially variable recharge have yet to reach a stage of practical application, though current research indicates some potential via a combination of selective ground truth data collection, geostatistics (autocorrelation and kriging) and remote sensing. Details of ongoing activities lie outside the scope of this manual introduction, but a series of interdependent sequential steps can be identified:

- determination of significant physiographic and hydrological parameters which may be used as simplifying surrogates to define the dynamics of the hydrological system (see Table 11.4);

- hydrological response unit identification by way of, for example, geometric grid cells and statistical analyses (Sivapalan and Wood, 1986; Hendriks, et al., 1987);
- 'regionalisation' of the digitised grid cell data using hydrologically oriented classification procedures, with subsequent application of specific recharge techniques and eventual models in each of the classified units.

A systematic approach of this type, based on the spatial scale of variability for measurable physical characteristics, will minimise areal recharge estimate uncertainty for a given expenditure on data collection. However, until these techniques have sufficiently evolved to be of value for practical model application, it would appear that to resolve the spatial variability problem there is little alternative to multiple site recharge estimation in the area of interest. These thoughts are developed further in the suggested procedure algorithm presented in Chapter 9 and in Section 11.7.

1.4 Resource management implications

An introduction to a manual on arid and semi-arid zone groundwater recharge estimation would be incomplete without some comment on associated implications for water resources management. In reality the issue is complex and for optimum value should be site specific, though a number of generalisations are evident from the literature. This section should thus be considered as a summary overview and draws heavily on the more detailed information presented by Lloyd (1986) and Foster (1988).

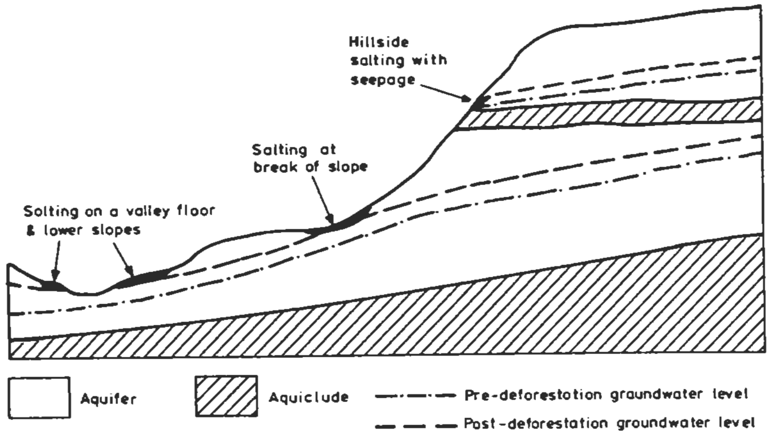

Fig. 1.6 Concepts of salination down the hydraulic gradient into progressively arid areas of Victoria, Australia, as a result of deforestation in the recharge area (Lloyd, 1986)

Two major recharge connected problems in arid and semi-arid area groundwater development are groundwater quality deterioration and resource overexploitation. An obvious example of the first problem would be the too frequently recorded increases in dissolved solids associated with poor agricultural and irrigation practices. Less immediately obvious are the long-term consequences of landuse changes in groundwater recharge areas. Fig. 1.6 (from Lloyd, 1986) is an Australian example of this situation, where severe dryland salination over large areas is a direct result of increased recharge following deforestation in the 19th century.

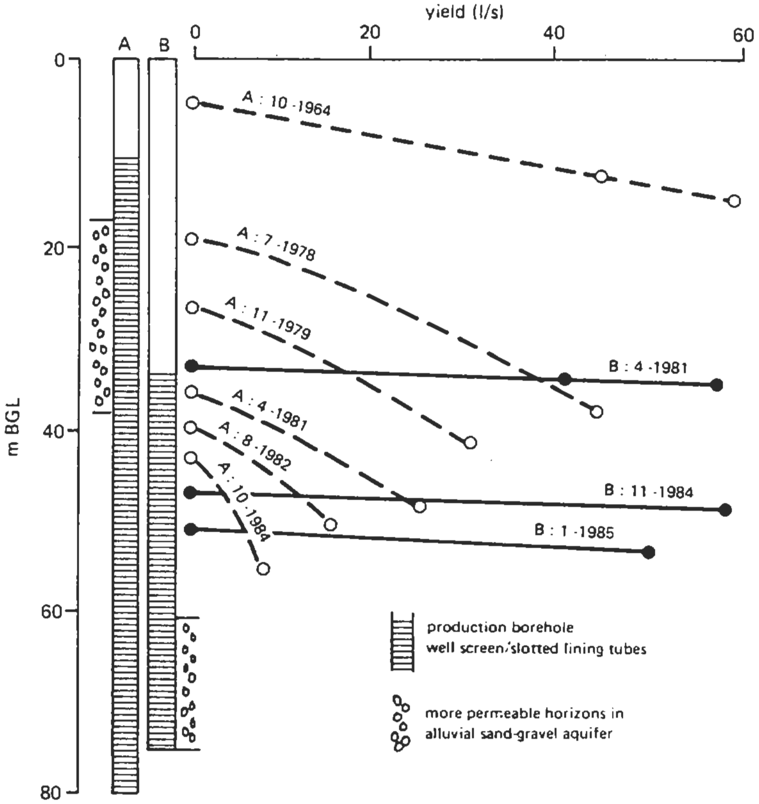

Fig. 1.7 Production performance of pumping boreholes in the overdeveloped alluvial fan aquifer of Lima, Peru (Foster 1988). The contrasting behaviour reflects the falling groundwater level and varying depth at which permeable horizons occur.

Since arid and semi-arid region recharge estimates are often subject to considerable uncertainty and large error, groundwater overdevelopment can occur if active recharge is overestimated. For example, it is not uncommon to find that model based resource evaluations initially overestimate recharge, the classical pattern shown by increasingly refined studies of an area being that of lower recharge values and hence smaller groundwater resources. A number of the consequences of recharge overestimation are listed by Foster (1988) to be:

- 'increased pumping costs, yield reductions and even complete failure of production boreholes (Fig. 1.7);
- the encroachment of saline water into freshwater aquifers in some coastal and inland basin situations;
- land subsidence consequent upon settlement of under-consolidated lacustrine, deltaic or estuarine sedimentary aquifers'.

However, groundwater mining can be an acceptable practice in arid areas provided it is carefully planned and controlled and subject to realistic ongoing evaluation.

A further groundwater resource development problem, particularly in developing countries, is that there are frequently inadequate data to permit reasonable calibration of any recharge model, thus introducing constraints to the assessment of management options. Since large-scale collection of additional data prior to project implementation is usually impractical for reasons of cost and required development timetable, both Lloyd (1986) and Foster (1988) strongly advocate adopting a flexible approach to project design and management. This implies that groundwater resource development should be staged, allowing progressive aquifer response data collection and resource evaluation. A further practical reason for such an approach is that understanding of the hydrogeological system is sometimes difficult until it is stressed. A conceptual framework for such a programme is illustrated by Fig. 1.8 and an example is given in Fig. 1.9.

Foster (1988) does state, however, that under some circumstances this approach will have a more limited application; viz, where

- 'the minimum viable first stage water demand is very large relative to exploitable aquifer storage;
- the profitability of proposed groundwater use is highly sensitive to energy costs;
- there is a significant risk of saline encroachment in an aquifer as a consequence of medium-term overdevelopment'.

1.5 Recharge requirements for groundwater modelling

It is clear from previous sections that groundwater recharge can be modelled at many scales for many different purposes. The required information on recharge varies in each case, that for pollution transport studies within a village on a hard rock aquifer being different from a groundwater resources project for a regional aquifer of 1000 km^2.

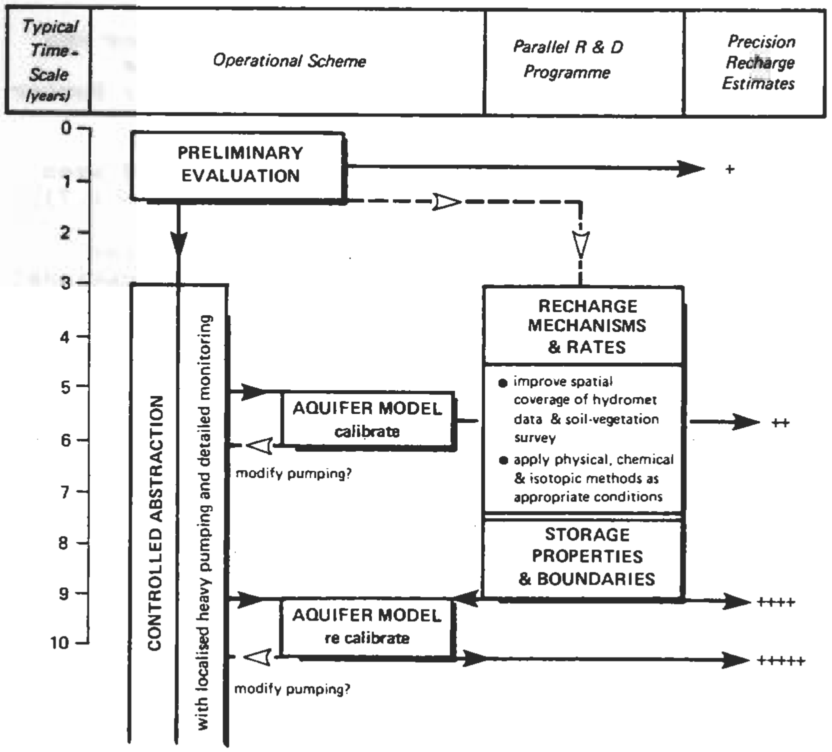

Fig. 1.8 Outline scheme for the integrated operational approach to improving estimates of aquifer recharge rates and storage parameters (Foster, 1988)

For resources studies interest is generally in both the total amount of recharge (since total recharge = replenishable resources) and its spatial and temporal variability (because the optimum use of resources depends upon their distribution). The amount of detail required about recharge variations is in turn governed by the degree to which groundwater resources are (to be) used, and upon the nature of the recharge processes. This means that if only 5% of the resources are used, less detail is needed concerning temporal variations; the aquifer storage will carry through a drought, and a modelling study using long-term average data will suffice.

There is also little point in regional models estimating recharge variation across areas of less than several nodes. In reality however, and for the sake of estimate precision, non-linearities of the recharge process may require values to be determined in more detail than would otherwise be needed for a model, with subsequent averaging over space and time prior to any simulation. Unfortunately data are often both scarce and short-term in arid and semi-arid areas, resulting in an erroneous spatial picture and recharge estimates which may be completely unrepresentative of the long-term pattern (see Section 1.3). In such instances the direct use of groundwater information can improve recharge determinations.

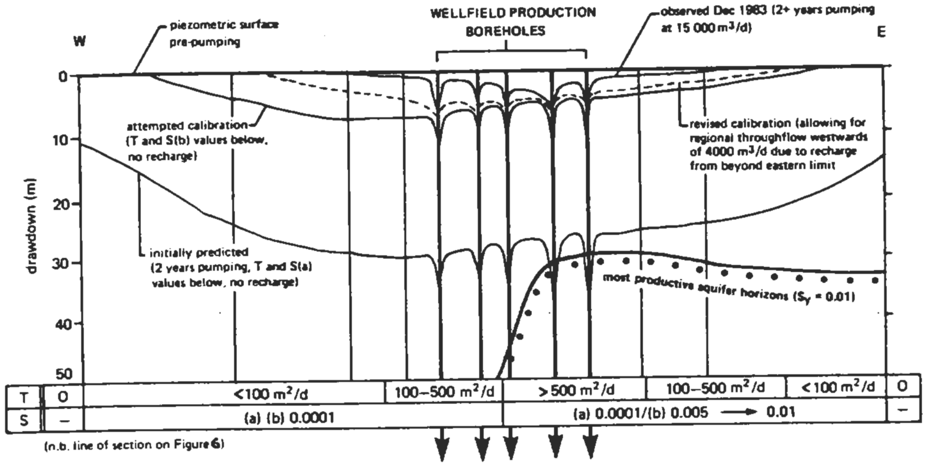

Fig. 1.9 Schematic cross-section of the Jwaneng northern wellfield, Botswana Kalahari, showing initital prediction of the aquifer numerical model and the calibration based on operational monitoring experience with revised storage and recharge parameters (Foster, 1988)

There are of course some cases when there will be minimum value in estimating groundwater recharge; for example, in a limited life scheme where demand will greatly exceed replenishable resources. In this case aquifer storage is of much greater importance than recharge and the system can be conservatively modelled with a zero recharge component. All efforts should thus go to estimating specific yield; any recharge which does occur will provide a safety factor towards the end of the project's life. A second case would be when recharge is low compared to throughflow. The uncertainties in geology, aquifer boundaries and properties, groundwater levels and even borehole abstractions are so great that although a few millimetres per year of recharge may be of great scientific interest, they will be of little water resources concern. On the other hand, in some instances even very small increases in groundwater recharge can have an important practical impact on other aspects of arid zone hydrogeology (e.g., (re-)activation of local springs).

Although the dangers of generalisation are obvious, an element in common to all water resources development decisions involving recharge is the need to initiate investigation programmes on the basis of a hydrogeological conceptual model - defined here as a description of the hydrogeological conditions including the distribution and properties of rocks and the flow of water. Such a conceptual model is the key to logical subsequent development of the most appropriate mathematical/numerical techniques.

1.6 Conclusions

Reliable estimation of groundwater recharge in arid and semi-arid areas is neither straightforward nor easy. Although quantitative information on recharge is often critical for optimum resource modelling and management, no single comprehensive estimation technique can yet be identified from the spectrum of methods available. Differences in sources and processes of recharge mean that the applicability of available procedures will differ, with significant practical implications attached to whether the derived results apply at a point or over a wider area.

The need to proceed from a well defined conceptualisation of different recharge processes is thus necessary, as is the need to use more than one technique for result verification - recharge estimation should thus be viewed as an iterative process, not as a once-and-for-all calculation. As concluded by Knutsson (1988), final choice of techniques will also be determined by the study objectives, initial data base and the possibilities to supplement this, and of course available financial resources.

Despite the spectrum of problems associated with groundwater recharge estimation, the chapters which follow guide both the general reader and practitioner in a structured fashion through the maze of pitfalls and options involved.