1 Groundwater modelling in arid and semi-arid areas: an introduction

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1.1 INTRODUCTION

Water resources globally face unprecedented challenges, but these are at their greatest in the world's arid and semi-arid regions. Recent IPCC estimates (Kundzewicz *et al.*, 2007) state that between 1.4 and 2.1 billion people live in areas of water stress; those numbers are expected to increase significantly under the pressures of population growth and climate change.

By definition, arid and semi-arid regions have limited natural water resources, and precipitation and runoff have very high variability in space and time. Traditional societies recognised these characteristics and developed sustainable water management solutions. In higher rainfall areas, for example in the mountains of northern Yemen and Greek islands such as Cephalonia, rainwater was harvested from roofs and paved surfaces and stored for household or community use. In desert areas, such as Arabia's 'empty quarter', with infrequent, spatially localised rainfall, nomadic communities would follow rainfall occurrence, using water from surface storage or shallow groundwater for a few months to support themselves and their livestock, before moving on. For agriculture, terraced systems were developed to focus infiltration to provide soil moisture for crop water needs (as in the mountains of Northern Oman and Yemen), and earth dams were built to divert flash floods onto agricultural land for surface irrigation (as in South West Saudi Arabia). In parts of the Middle East, groundwater was extracted sustainably using qanats (Iran) or afalaj (Oman), ancient systems of tunnels for gravity drainage of groundwater, developed over centuries or longer.

The twentieth century has seen pressures of increased population, increased social expectations for domestic use and increased agricultural water use, and the general result has been unsustainable use of water, from the developed and wealthy economies of Southwestern USA, to poorer countries of South America, Africa, Asia and the Middle East. This has led to declining groundwater levels, reduced (or non-existent) surface-water flows and loss of wetlands, such as the Azraq oasis in North East Jordan – a RAMSAR wetland site now totally dry due to over-pumping of groundwater. There is a range of adverse effects associated with this over-exploitation, for example, loss of important habitats, deteriorating water quality, including ingress of saline water in coastal aquifers, and land subsidence. In the twenty-first century we face the added challenge of climate change. It is essential therefore that we recognise the need for sustainable use of water, balancing the long-term use with the long-term water availability, and learn to use best practice from traditional and new methods of water management. This requires social recognition of water scarcity, the political will to confront difficult societal choices, and good science and engineering to develop and support sustainable management solutions.

This book has been developed under UNESCO's G-WADI programme and aims to provide state-of-the-art guidance for those involved in water science and management in arid and semi-arid areas concerning the modelling methods that are needed to characterise water resource systems and their sustainable yield, and to provide protection from pollution. In an earlier book (Wheater *et al.*, 2008), G-WADI mainly addressed the issues of surface-water systems. Here we consider groundwater.

1.2 GROUNDWATER RESOURCES AND MODELLING NEEDS IN ARID AND SEMI-ARID AREAS

Groundwater is commonly the most important water resource in arid areas. In areas of high evaporation and limited rainfall, groundwater provides natural storage of water which is protected from surface evaporation, it is spatially distributed, and it can be developed with limited capital expenditure. Groundwater also provides a potential storage that can be managed to increase the useful water resource. One example is the use of recharge

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dams, as developed on the coastal (Batinah) plain of the Sultanate of Oman, to temporarily retain flash floods and focus the infiltration of surface water to recharge the underlying aquifer system. A recent review of aspects of Managed Aquifer Recharge (MAR) can be found in Dillon *et al*., (2009).

However, as noted above, in all arid regions, groundwater resources are under threat from over-abstraction and pollution. The widescale deployment of powerful motorised pumps, in the absence of effective regulation, has led to major problems of resource depletion, declining water levels and deterioration of water quality. A particular and widespread problem arises where over-abstraction in coastal aquifers leads to ingress of salt water, which can make the resource unusable (see Chapter 7). And the time-scales of groundwater response are such that pollution may affect a resource for decades or centuries, if indeed full recovery is possible. Moreover, in some areas much of the water being abstracted from deep aquifers is non-renewable, being a legacy from wetter climates in the past.

Management of aquifers must make best use of available information and balance competing pressures. However, the ability to observe the subsurface is limited, and hence characterisation of available groundwater resources, and in particular the natural recharge that sustains these resources, is difficult and often highly uncertain. Models are therefore used worldwide as a tool to assimilate data on groundwater systems and to guide decisions on management strategies for groundwater resources and protection from, and remediation of, pollution. It is the aim of this book to provide insight into the modelling process, the integration of data sources and the issues of sustainable management of groundwater in the context of the special needs of arid and semi-arid areas.

1.3 THE BOOK CONTENT AND STRUCTURE

Chapter 2 summarises current knowledge of hydrological processes in arid and semi-arid areas, including rainfall, runoff, surface-water–groundwater interactions (including wadi-bed transmission losses) and groundwater recharge, drawing on examples from the Middle East, southern Africa and the USA. There is limited guidance in the scientific and technical literature on the hydrology of arid areas or on the modelling tools needed to underpin groundwater management.

The hydrology of arid areas is very different from that of humid areas, and Chapter 2 outlines the special technical challenges in the assessment and management of water. Precipitation is a particular problem. It is generally characterised by very high variability in space and time; runoff from a single large storm can exceed the total runoff from a sequence of years, and intense rainfall can be spatially localised. Flows are infrequent but times to peak are typically short and discharges can be large. Flows often decrease with distance downstream as water is lost to channel bed infiltration. Hydrological data from such areas are difficult to capture and available records are limited in length and quality. Rainfall and flood events are thus difficult to quantify, and this leads to difficulty in rainfall–runoff modelling and in the estimation of groundwater recharge. It is argued that distributed modelling is needed to capture the spatial variability of precipitation, runoff and recharge processes, to quantify groundwater recharge and to assess the potential for recharge management. Given the lack of data, integrated modelling of surface and groundwater systems is needed to assimilate the available data and inform management decisions.

Chapter 3 introduces the use of isotopic and geochemical methods in the analysis of groundwater systems in arid and semi-arid areas. This includes methods of investigation, time-scales and palaeohydrology, rainfall and unsaturated zone chemistry, and the hydrochemistry of groundwater systems in arid and semi-arid areas. Chemical and especially isotopic methods can provide valuable insights into groundwater systems and their functioning. The development of water quality may be viewed as an evolution over time, for example: (i) undisturbed evolution under natural conditions; (ii) the development phase with some disturbance of natural conditions, especially stratification; (iii) development with contamination; and (iv) artificially managed systems. Hence the methods can identify the interface between modern water and palaeowaters as a basis for sustainable management of water resources. Chapter 3 focuses on the use of isotopic and geochemical methods to assist the development of conceptual models for recharge sequences. The application of hydrogeochemical techniques in understanding the water quality problems of semi-arid regions is described and follows the chemical pathway of water from rainfall through the hydrological cycle. A number of case studies from Sudan, Nigeria and Senegal as well as North African counties and China are used to illustrate the main principles.

Chapter 4 sets out the basic strategy for modelling groundwater flow and transport processes, including modelling objectives and modelling procedure (including conceptualisation, calibration and error analysis, model selection, predictions and uncertainty), and introduces advanced methods to represent spatial variability (kriging, conditional simulation, sequential Gaussian simulation and facies simulation), and advanced methods of calibration and uncertainty propagation. Groundwater modelling involves a range of complex issues from understanding site geology to the development and application of suitable numerical methods. Chapter 4 has been arranged to cover the basics of these while directing the reader to specialised literature for details. The chapter starts by describing the flow phenomenon in terms of equations and basic numerical methods. This is followed by a discussion on the general procedure of building models using numerical codes. Since heterogeneity is such a ubiquitous problem, the chapter dedicates a large section to describing many of the basic geostatistical and upscaling tools available to deal with spatial variability. From here, a formalisation of the calibration procedure is made. Finally, the chapter concludes with a discussion on methods for uncertainty assessment.

In most situations, observed groundwater and associated data are sparsely distributed within the area of interest. The study of regionalised variables starts from the ability to interpolate a given field from only a limited number of observations while preserving the theoretical spatial correlation. This is often accomplished by means of a geostatistical technique called kriging. Compared with other interpolation techniques, kriging is advantageous because it considers the number and spatial configuration of the observation points, the position of the data point within the region of interest, the distances between the data points with respect to the area of interest and the spatial continuity of the interpolated variable. Chapter 5 further describes the theory of regionalised variables and how it can be applied to groundwater modelling studies. The discussed techniques are then demonstrated through a case study from the Maheshwaram watershed of Andhra Pradesh, India.

As discussed above, groundwater resources are vulnerable to pollution. This may be either from point sources, for example illegal or accidental discharges from industry or domestic wastes, or from diffuse pollution, as in the case of nutrient pollution from agriculture. It is a characteristic of groundwater systems that remediation of pollution is difficult, costly and time-consuming, and may only be partially successful. There are therefore strong societal imperatives to protect groundwater resources. Chapter 6 addresses this issue. First, the techniques available for the assessment of aquifer vulnerability are presented, considering their relative advantages and disadvantages, and their applications to the particular characteristics of arid and semi-arid areas. Second, the definition of protection zones for individual water sources is discussed. This requires definition of either a total catchment area for a well, or a time-related capture zone, i.e. defining the time of travel of potential pollutants to a given source. Again, applications to arid and semi-arid areas are discussed, including detailed methodologies to specify flow pathways and pollutant travel times, and simpler rules of thumb relevant, for example, to the relative siting of wells and pit latrines.

Arid and semi-arid climates are mainly characterised as those areas where precipitation is less (and often considerably less) than potential evapotranspiration. These climate regions are ideal environments for salt to accumulate in natural soil and groundwater settings since evaporation and transpiration remove freshwater from the system, leaving residual salts behind. Similarly, the characteristically low precipitation rates reduce the potential for salt to be diluted by rainfall. Salt flats, playas, sabkhas and saline lakes, for example, are therefore ubiquitous features of arid and semi-arid regions throughout the world. In such settings, variable density flow phenomena are expected to be important, especially where hypersaline brines overlie less dense groundwater at depth. In coastal regions, sustainable management of groundwater resources must also take into account the variable density phenomena of seawater intrusion. Chapter 7 provides a comprehensive state-of-the-art review of the issues of modelling density-dependent flows. The importance of density-dependent flows for arid regions is discussed, variable density physics is introduced, the relevant governing equations for simulating variable density flow are presented and various commercial numerical codes are compared. Model benchmarking is discussed in detail. Applications and case studies include seawater intrusion and tidally induced phenomena, transgression–regression salinisation of coastal aquifers, aquifer storage and recovery, fractured rock flow and chemically reactive transport modelling.

As a result of the ever-growing global population, pressure on water resources is increasing continually. In many cases, the presently applied management practices are non-sustainable and lead to serious water-related problems such as the depletion of aquifers and the accumulation of substances to harmful levels, as well as to water conflicts or economically infeasible costs. Chapter 8, as the final chapter, addresses sustainable water management in arid and semi-arid regions. Associated problems are poignantly illustrated by case studies. The northwest Sahara aquifer system is used to show the consequences of the overpumping of aquifers, and a typical upstream–downstream problem is discussed with the example of the Okavango delta. Another case study discussed is the Yanqi basin in China. The Yanqi basin is a typical example showing how inappropriate irrigation practices can lead to soil salinisation and ecological problems downstream. This final chapter clearly demonstrates the important role numerical modelling can play as a tool to develop sustainable groundwater management practices. Some of the most common problems in setting up reliable models are highlighted and ideas on how to address these problems are given. Useful guidance is also given to help narrow the often prevalent gap between scientists and decision makers.

1.4 CONCLUSIONS

Groundwater lies at the heart of many of the water management issues faced in arid and semi-arid regions. In this book we attempt to provide some insight into the tools and techniques available to support the sustainable management of groundwater resources. Assessment of recharge is fundamental to the definition of sustainable groundwater yields, yet this remains a very challenging area, particularly for arid and semi-arid areas. We present isotopic and geochemical methods that can be used for recharge estimation, and argue that modelling provides an essential set of tools for the integration of information on groundwater systems. We provide a state-of-the-art assessment of groundwater flow and quality modelling methods, with recent developments in the representation of uncertainty, including geostatistical methods. We provide methodologies for the protection of groundwater resources, through aquifer vulnerability assessment and the definition of well-capture areas. In dry areas, salinity is commonly a major issue, not only for saline intrusion in coastal aquifers, but more generally for water bodies in a high-evaporation environment. The implications for modelling and analysis can be profound, and we present a comprehensive discussion of the associated modelling capabilities and some outstanding research challenges. The book draws on a wide range of case study examples to illustrate the methods presented, and concludes with a final chapter that discusses the practical issues of modelling for decision support, and the important role of models as a means of communication between different stakeholders in the water management arena.

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2 Hydrological processes, groundwater recharge and surface-water/groundwater interactions in arid and semi-arid areas

H. S. Wheater

2.1 GROUNDWATER RESOURCES, GROUNDWATER MODELLING AND THE QUANTIFICATION OF RECHARGE

The traditional development of water resources in arid areas has relied heavily on the use of groundwater. Groundwater uses natural storage, is spatially distributed and, in climates where potential evaporation rates can be of the order of metres per year, provides protection from the high evaporation losses experienced by surface-water systems. Traditional methods for the exploitation of groundwater have been varied, including the use of very shallow groundwater in seasonally replenished riverbed aquifers (as in the sand rivers of Botswana), the channelling of unconfined alluvial groundwater in afalaj (or qanats) in Oman and Iran, and the use of hand-dug wells. Historically, abstraction rates were limited by the available technology, and rates of development were low, so that exploitation was generally sustainable.

However, in recent decades, pump capacities have dramatically increased and hence agricultural use of water has grown rapidly, while the increasing concentration of populations in urban areas has meant that large-scale well fields have been developed for urban water supply. A common picture in arid areas is that groundwater levels are in rapid decline; in many instances this is accompanied by decreasing water quality, particularly in coastal aquifers where saline intrusion is a threat. Associated with population growth, economic development and increased agricultural intensification, pollution has also become an increasing problem. The integrated assessment and management of groundwater resources is essential so that aquifer systems can be protected from pollution and over-exploitation. This requires the use of groundwater models as a decision support tool for groundwater management.

Some of the most difficult aspects of groundwater modelling concern the interaction between surface-water and groundwater systems. This is most obviously the case for the quantification of long-term recharge, which ultimately defines sustainable yields. Quantification of recharge remains the major challenge for groundwater development worldwide, but is a particular difficulty in arid areas where recharge rates are small, both as a proportion of the water balance and in absolute terms. However, more generally, the interactions between surface-water and groundwater systems are important. In arid areas, infiltration from surface-water channels, as a 'transmission loss' for surface flows, may be a major component of groundwater recharge, and there is increasing interest in the active management of this process to focus recharge (for example, in an extensive programme of construction of 'recharge dams' in northern Oman). Conversely, the discharge of groundwater to surface-water systems can be important in terms of valuable ecosystems. Hence the main thrust of this chapter is to review hydrological processes in arid and semi-arid areas, to provide the context for surface/groundwater interactions, and their analysis and modelling.

2.2 HYDROLOGICAL PROCESSES IN ARID AREAS

Despite the critical importance of water in arid and semi-arid areas, hydrological data have historically been severely limited. It has been widely stated that the major limitation of the development of arid zone hydrology is the lack of high-quality observations (McMahon, 1979; Nemec and Rodier, 1979; Pilgrim *et al.*, 1988). There are many good reasons for this. Populations are usually sparse and economic resources limited; in addition the climate is harsh and hydrological events infrequent but damaging. However, in the general absence of reliable long-term data and experimental research, there has been a tendency to rely on humid zone experience and modelling tools, and data from other regions. At best, such results will be highly inaccurate. At worst,

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Table 2.1. *Summary of Muscat rainfall data (1893–1959) (after Wheater and Bell, 1983).*

Monthly rainfall (mm)	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Mean	31.2	19.1	13.1	8.0	0.38	1.31	0.96	0.45	0.0	2.32	7.15	22.0
Standard deviation	38.9	25.1	18.9	20.3	1.42	8.28	4.93	2.09	0.0	7.62	15.1	35.1
Max.	143.0	98.6	70.4	98.3	8.89	64.0	37.1	14.7	0.0	44.5	77.2	171.2
Mean number of raindays	2.03	1.39	1.15	0.73	0.05	0.08	0.10	0.07	0.0	0.13	0.51	1.6
Max. daily fall (mm)	78.7	57.0	57.2	51.3	8.9	61.5	30.0	10.4	0.0	36.8	53.3	57.2
Number of years on record	63	64	62	63	61	61	60	61	61	60	61	60

there is a real danger of adopting inappropriate management solutions which ignore the specific features of dryland response.

Despite the general data limitations, there has been some substantial and significant progress in development of national data networks and experimental research. This has given new insights, and we can now see with greater clarity the unique features of arid zone hydrological systems and the nature of the dominant hydrological processes. This provides an important opportunity to develop methodologies for flood and water resource management which are appropriate to the specific hydrological characteristics of arid areas and the associated management needs, and hence to define priorities for research and hydrological data. The aim here is to review this progress and the resulting insights, and to consider some of the implications.

2.2.1 Rainfall

Rainfall is the primary hydrological input, but rainfall in arid and semi-arid areas is commonly characterised by extremely high spatial and temporal variability. The temporal variability of point rainfall is well known. Although most records are of relatively short length, a few are available from the nineteenth century. For example, Table 2.1 presents illustrative data from Muscat (Sultanate of Oman) (Wheater and Bell, 1983), which shows that a wet month is one with one or two raindays. Annual variability is marked and observed daily maxima can exceed annual rainfall totals.

For spatial characteristics, information is much more limited. Until recently, the major source of detailed data has been from Southwestern USA, most notably the two relatively small, densely instrumented basins of Walnut Gulch, Arizona (150 km^2), and Alamogordo Creek, New Mexico (174 km^2), established in the 1950s (Osborn *et al*., 1979). The dominant rainfall for these basins is convective; at Walnut Gulch 70% of annual rainfall occurs from purely convective cells, or from convective cells developing along weak, fast-moving cold fronts, and falls in the period July to September (Osborn and Reynolds, 1963). Raingauge densities were increased at Walnut Gulch to give improved definition of detailed storm structure and are currently better than 1 per 2 km^2. This has shown highly localised rainfall occurrence, with spatial correlations of storm rainfall of the order of 0.8 at 2 km separation, but close to zero at 15–20 km spacing. Osborn *et al*. (1972) estimated that to observe a correlation of $r^2 = 0.9$ raingauge spacings of 300–500 m would be required.

Recent work has considered some of the implications of the Walnut Gulch data for hydrological modelling. Michaud and Sorooshian (1994) evaluated problems of spatial averaging for rainfall-runoff modelling in the context of flood prediction. Spatial averaging on a 4 km × 4 km pixel basis (consistent with typical weather radar resolution) gave an underestimation of intensity and led to a reduction in simulated runoff of on average 50% of observed peak flows. A sparse network of raingauges (1 per 20 km^2), representing a typical density of flash flood warning systems, gave errors in simulated peak runoff of 58%. Evidently there are major implications for hydrological practice; we will return to this issue below.

The extent to which this extreme spatial variability is characteristic of other arid areas has been uncertain. Anecdotal evidence from the Middle East underlays comments that spatial and temporal variability was extreme (Food and Agriculture Organization, 1981), but data from southwest Saudi Arabia obtained as part of a five-year intensive study of five basins (Saudi Arabian Dames and Moore, 1988) undertaken on behalf of the Ministry of Agriculture and Water, Riyadh, have provided a quantitative basis for assessment. The five study basins range in area from 456 to 4930 km^2 and are located along the Asir escarpment (Figure 2.1), three draining to the Red Sea and two to the interior towards the Rub al Khali. The mountains have elevations of up to 3000 m above sea level (a.s.l.); hence the basins encompass a wide range of altitude, which is matched by a marked gradient in annual rainfall from 30–100 mm on the Red Sea coastal plain to up to 450 mm at elevations in excess of 2000 m a.s.l.

The spatial rainfall distributions are described by Wheater *et al*. (1991a). The extreme spottiness of the rainfall is illustrated for the 2869 km^2 Wadi Yiba by the frequency distributions of the number of gauges at which rainfall was observed given the occurrence of a catchment rainday (Table 2.2). Typical intergauge spacings were 8–10 km, and on 51% of raindays only one or two raingauges out of 20 experienced rainfall. For the more widespread events, subdaily rainfall showed an even more spotty

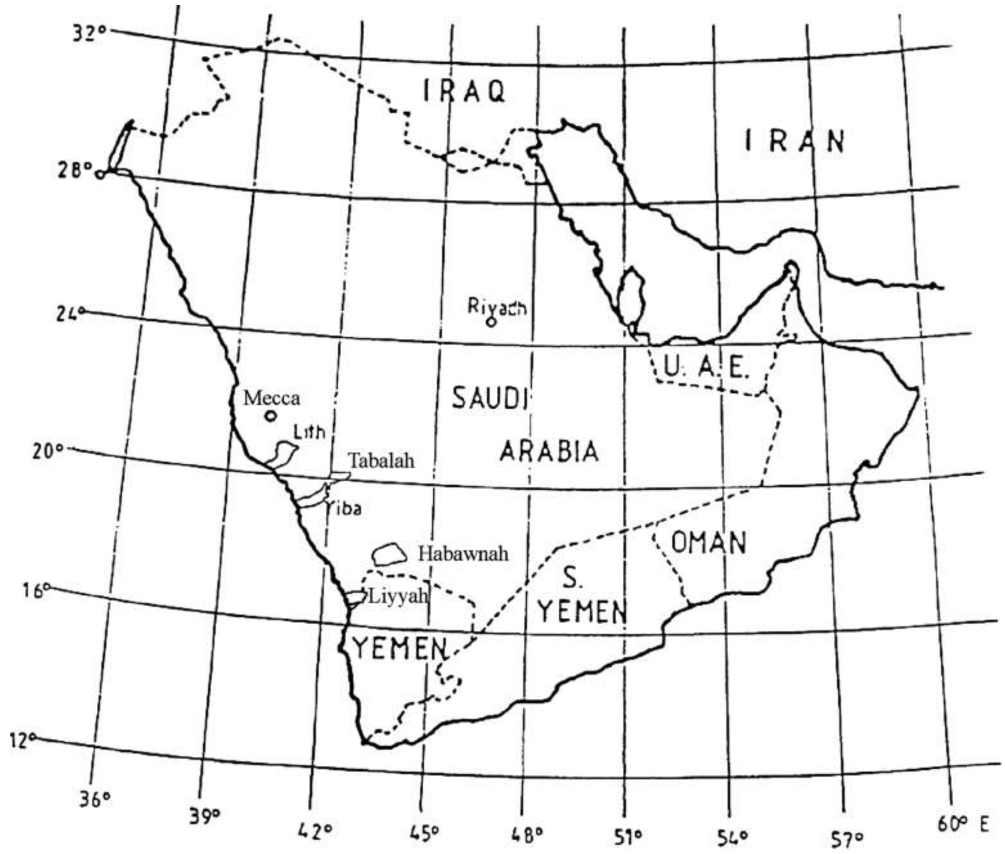

Figure 2.1. Location of Saudi Arabian study basins.

Table 2.2. *Wadi Yiba raingauge frequencies and associated conditional probabilities for catchment rainday occurrence.*

Number of gauges	Occurrence	Probability
1	88	0.372
2	33	0.141
3	25	0.106
4	18	0.076
5	10	0.042
6	11	0.046
7	13	0.055
8	6	0.026
9	7	0.030
10	5	0.021
11	7	0.030
12	5	0.021
13	3	0.013
14	1	0.004
15	1	0.004
16	1	0.005
17	1	0.004
18	1	0.004
19	0	0.0
20	0	0.0
TOTAL	235	1.000

picture than the daily distribution. An analysis of relative probabilities of rainfall occurrence, defined as the probability of rainfall occurrence for a given hour at station B given rainfall at station A, gave a mean value of 0.12 for Wadi Yiba, with only 5% of values greater that 0.3. The frequency distribution of rainstorm durations shows a typical occurrence of one- or two-hour duration point rainfalls, and these tend to occur in mid to late afternoon. Thus rainfall will occur at a few gauges and die out, to be succeeded by rainfall in other locations. This is illustrated for Wadi Lith in Figure 2.2, which shows the daily rainfall totals for the storm of 16 May 1984 (Figure 2.2a), and the individual hourly depths (Figures 2.2b–e). In general, the storm patterns appear to be consistent with the results from Southwest USA, and area reduction factors were also generally consistent with results from that region (Wheater *et al.*, 1989).

The effects of elevation were investigated, but no clear relationship could be identified for intensity or duration. However, a strong relationship was noted between the frequency of raindays and elevation. It was thus inferred that, once rainfall occurred, its point properties were similar over the catchment, but occurrence was more likely at the higher elevations. It is interesting to note that a similar result has emerged from an analysis of rainfall in Yemen (UNDP, 1992), in which it was concluded that daily rainfalls observed at any location are

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effectively samples from a population that is independent of position or altitude.

It is dangerous to generalise from samples of limited record length, but it is clear that most events observed by those networks are characterised by extremely spotty rainfall, so much so that in the Saudi Arabian basins there were examples of wadi flows generated from zero observed rainfall. However, there were also some indications of a small population of more widespread rainfalls, which would obviously be of considerable importance in terms of surface flows and recharge. This reinforces the need for long-term monitoring of experimental networks to characterise spatial variability.

For some other arid or semi-arid areas, rainfall patterns may be very different. For example, data from arid New South Wales, Australia, have indicated spatially extensive low-intensity rainfalls (Cordery *et al.*, 1983), and recent research in the Sahelian zone of Africa has also indicated a predominance of widespread rainfall. This was motivated by concern to develop improved understanding of land-surface processes for climate studies and modelling, which led to a detailed (but relatively short-term) international experimental programme, the HAPEX-Sahel project based on Niamey, Niger (Goutorbe *et al.*, 1997). Although designed to study land surface/atmosphere interactions, rather than as an integrated hydrological study, it has given important information. For example, Lebel *et al.* (1997) and Lebel and Le Barbe (1997) note that a 100 raingauge network was installed and report information on the classification of storm types, spatial and temporal variability of seasonal and event rainfall, and storm movement. It was found that 80% of total seasonal rainfall fell as widespread events which covered at least 70% of the network. The number of gauges allowed the authors to analyse the uncertainty of estimated areal rainfall as a function of gauge spacing and rainfall depth.

Recent work in southern Africa (Andersen *et al.*, 1998; Mocke, 1998) has been concerned with rainfall inputs to hydrological models to investigate the resource potential of the sand rivers of northeast Botswana. Here, annual rainfall is of the order of 600 mm, and available rainfall data is spatially sparse and apparently highly variable but of poor data quality. Investigation of the representation of spatial rainfall for distributed water resource modelling showed that use of conventional methods of spatial weighting of raingauge data, such as Theissen

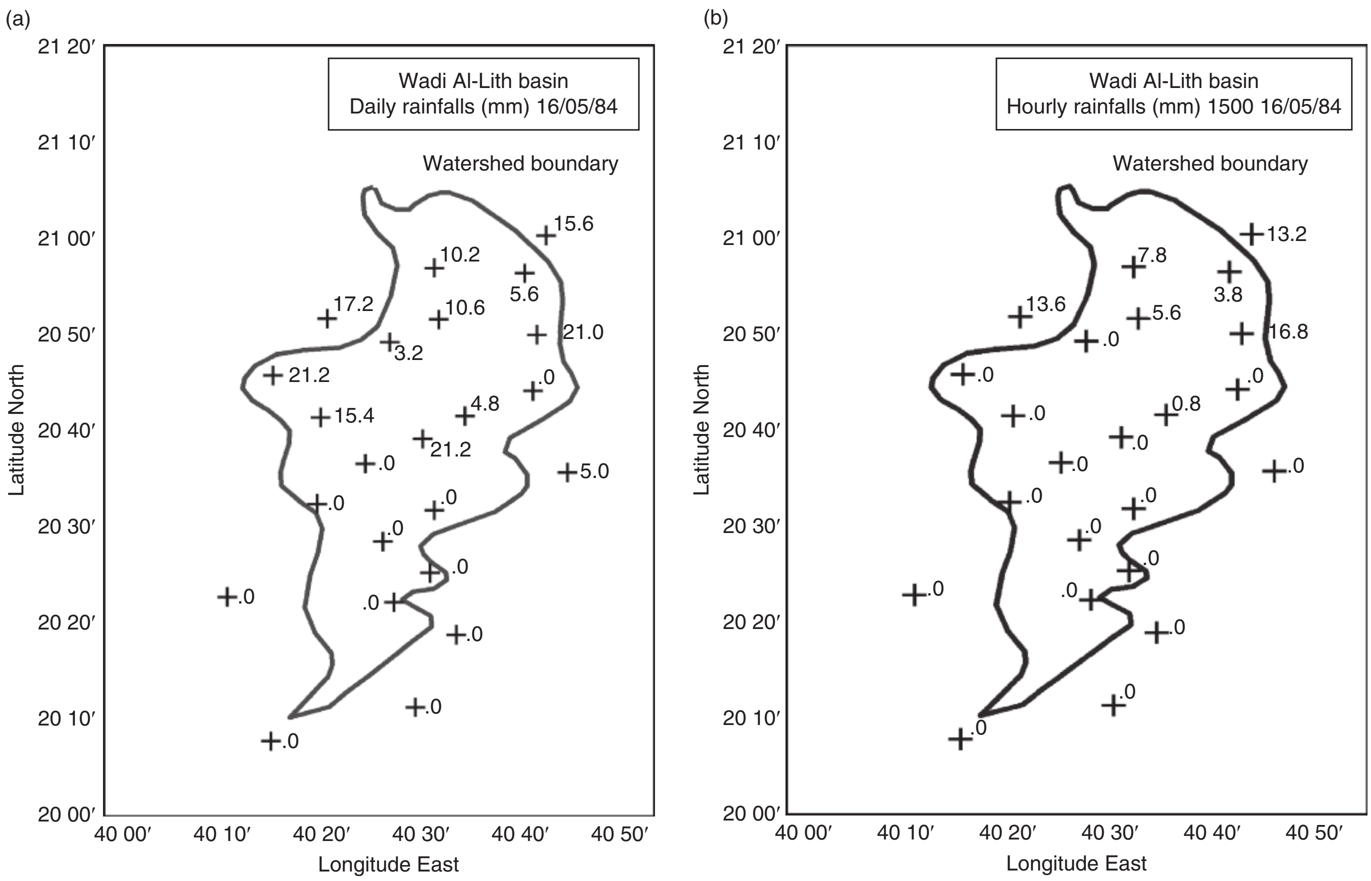

Figure 2.2. Wadi Al-Lith (a) daily and (b)–(e) hourly rainfall, 16 May 1984.

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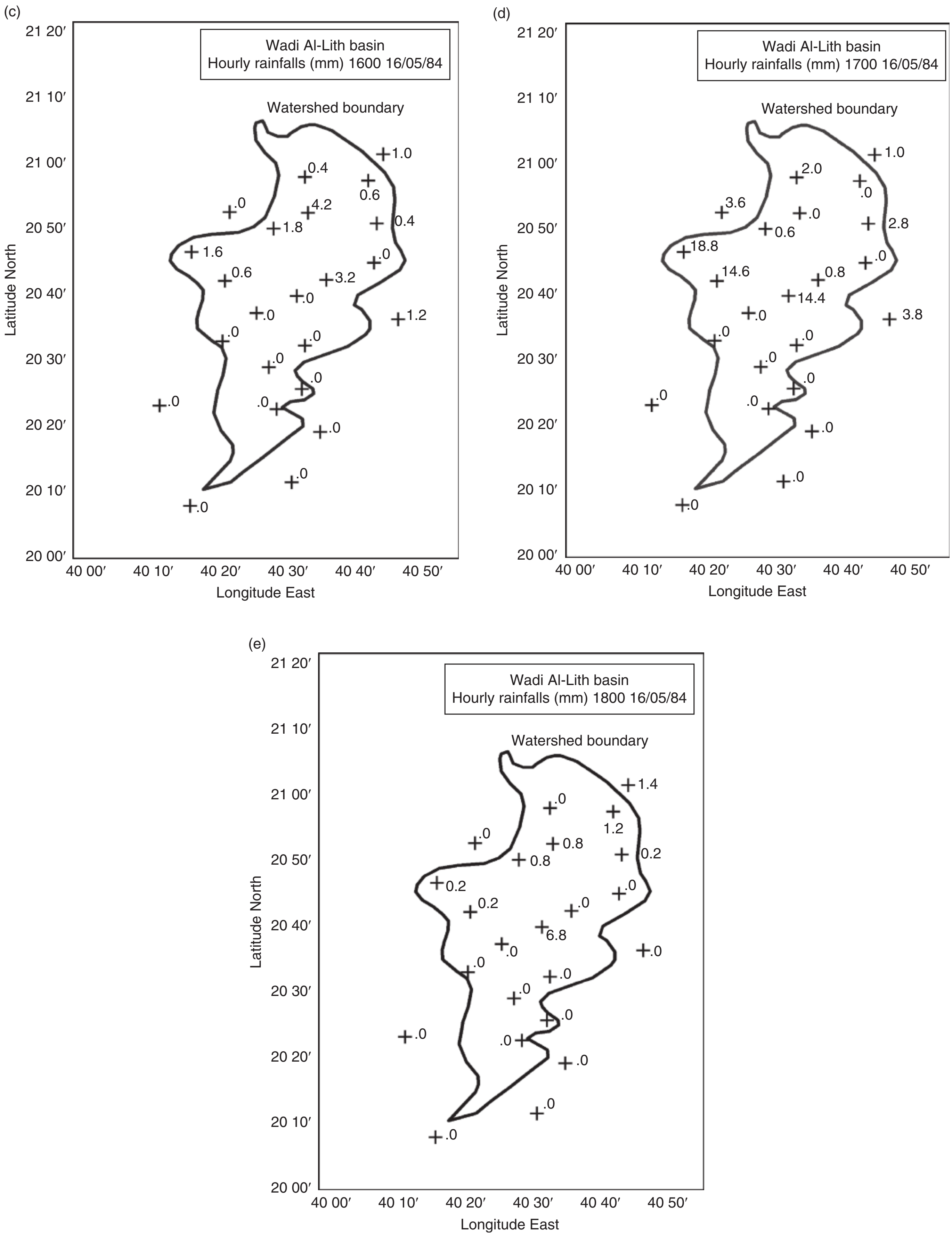

Figure 2.2. (cont.)

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polygons, could give large errors. Large sub-areas had rainfall defined by a single possibly inaccurate gauge. A more robust representation resulted from assuming catchment-average rainfall to fall uniformly, but the resulting accuracy of simulation was still poor. Al-Qurashi *et al*. (2008) report application of the KINEROS2 rainfall-runoff model to a catchment in Oman. Rainfall spatial variability was a dominant influence on performance, and McIntyre *et al*. (2007) show that simple empirical relationships can be at least as successful in representing hydrograph characteristics.

2.2.2 Rainfall-runoff processes

The lack of vegetation cover in arid and semi-arid areas removes protection of the soil from raindrop impact, and soil crusting has been shown to lead to a large reduction in infiltration capacity for bare soil conditions (Morin and Benyamini, 1977); hence infiltration of catchment soils can be limited. In combination with the high-intensity short-duration convective rainfall discussed above, extensive overland flow can be generated. This overland flow, concentrated by the topography, converges on the wadi channel network, with the result that a flood flow is generated. However, the runoff generation process due to convective rainfall is likely to be highly localised in space, reflecting the spottiness of the spatial rainfall fields, and to occur on only part of a catchment, as illustrated above.

Linkage between inter-annual variability of rainfall, vegetation growth and runoff production may occur. Our modelling in Botswana suggests that runoff production is lower in a year which follows a wet year, due to enhanced vegetation cover, which supports observations reported by Hughes (1995).

Commonly, flood flows move down the channel network as a flood wave, moving over a bed that either is initially dry or has a small initial flow. Hydrographs are typically characterised by extremely rapid rise times of as little as 15–30 minutes (Figure 2.3). However, losses from the flood hydrograph through bed infiltration are an important factor in reducing the flood volume as the flood moves downstream. These transmission losses dissipate the flood and obscure the interpretation of observed hydrographs. It is not uncommon for no flood to be observed at a gauging station, when further upstream a flood has been generated and lost to bed infiltration.

As noted above, the spotty spatial rainfall patterns observed in Arizona and Saudi Arabia are extremely difficult, if not impossible, to quantify using conventional densities of raingauge network. This, taken in conjunction with the flood transmission losses, means that conventional analysis of rainfall-runoff relationships is problematic, to say the least. Wheater and Brown (1989) present an analysis of Wadi Ghat, a 597 km^2 subcatchment of Wadi Yiba, one of the Saudi Arabian basins discussed

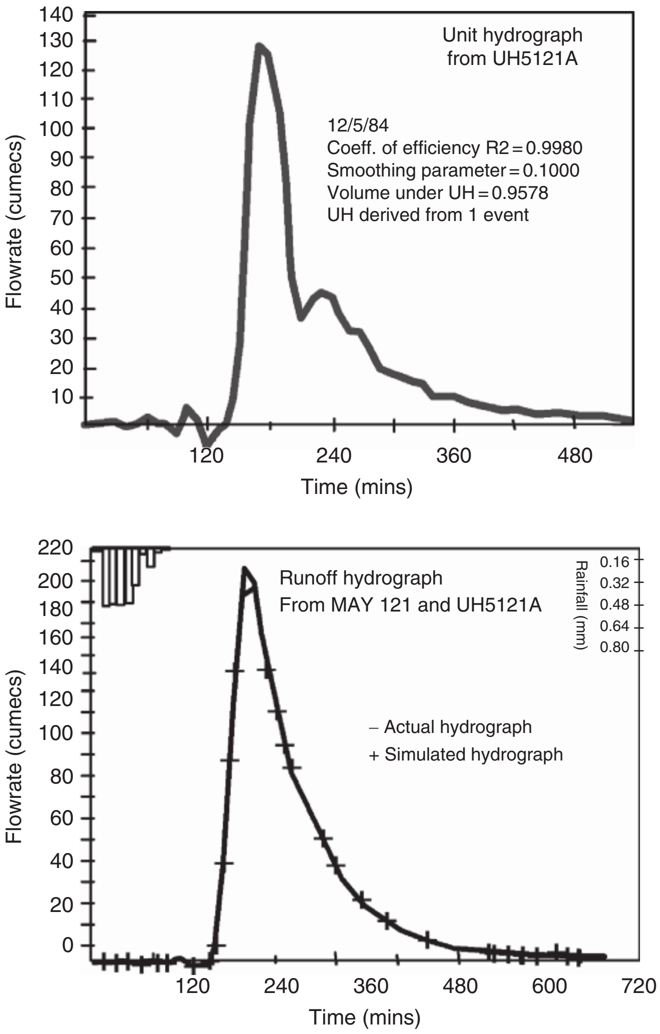

Figure 2.3. Surface-water hydrographs, Wadi Ghat 12 May 1984: observed hydrograph and unit hydrograph simulation.

above. Areal rainfall was estimated from five raingauges and a classical unit hydrograph analysis was undertaken. A striking illustration of the ambiguity in observed relationships is the relationship between observed rainfall depth and runoff volume (Figure 2.4). Runoff coefficients ranged from 5.9 to 79.8%, and the greatest runoff volume was apparently generated by the smallest observed rainfall! Goodrich *et al*. (1997) show that the combined effects of limited storm areal coverage and transmission loss give important differences from more humid regions. Whereas generally basins in more humid climates show increasing linearity with increasing scale, the response of Walnut Gulch becomes more non-linear with increasing scale. It is argued that this will give significant errors in application of rainfall depth–area–frequency relationships beyond the typical area of storm coverage, and that channel routing and transmission loss must be explicitly represented in watershed modelling.