# 1 Modelling hydrological processes in arid and semi-arid areas: an introduction to the workshop

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## 1.1 INTRODUCTION

In the arid and semi-arid regions of the world, water resources are limited, and under severe and increasing pressure due to expanding populations, increasing per capita water use and irrigation. Point and diffuse pollution, increasing volumes of industrial and domestic waste, and over-abstraction of groundwater provide a major threat to those scarce resources. Floods are infrequent, but extremely damaging, and the threat from floods to lives and infrastructure is increasing, due to urban development. Ecosystems are fragile, and under threat from groundwater abstractions and the management of surface flows. Added to these pressures is the uncertain threat of climate change. Clearly, effective water management is essential, and this requires appropriate decision support systems, including modelling tools.

Modelling methods have been widely used for over 40 years for a variety of purposes, but almost all modelling tools have been primarily developed for humid area applications. Arid and semi-arid areas have particular challenges that have received little attention. One of the primary aims of this workshop is to bring together world-wide experience and some of the world's leading experts to provide state-of-the-art guidance for modellers of arid and semi-arid systems.

The development of models has gone hand-in-hand with developments in computing power. While event-based models originated in the 1930s and could be used with hand calculation, the first hydrological models for continuous simulation of rainfall-runoff processes emerged in the 1960s, when computing power was sufficient to represent all of the land-phase processes in a simplified, "conceptual" way. Later, in the 1970s and 1980s, increases in power enabled "physically based" hydrological models to be developed, solving a coupled set of partial differential equations to represent overland, in-stream, and subsurface flow and transport processes, together with evaporation from land and water surfaces. And currently, global climate models are able to represent the global hydrological cycle with simplified physics-based models. In parallel, recent developments in computer power provide the ability to use increasingly powerful methods for the analysis of model performance and to specify the uncertainty associated with hydrological simulations. There have, as a result, been important developments in our understanding of modelling strengths and limitations. The workshop will present a range of modelling approaches and introduce methods of uncertainty analysis.

The relationship between models and data is fundamental to the modelling task. Current technology and computing power can provide powerful pre- and post-processors for hydrological models through Geographic Information Systems, linking with digital data sets to provide a user-friendly modelling environment. Some of these methods will be demonstrated here, and an important issue for discussion is the extent to which such methods are applicable to data-sparse environments, and for countries where the underlying digital data may be hard to obtain. Global developments in remote sensing, coupled with modelling and data assimilation, are providing new sources of information. For example, precipitation estimates for mid-latitudes are now available in near real-time; remote sensing of water body elevation is approaching the point where resolution is useful for real-time hydrological modelling. Again, the workshop will illustrate new data products and discuss their applicability (see Chapter 2 by Sorooshian *et al.*).

This introductory chapter aims to set the scene with a perspective on the strengths and weaknesses of alternative modelling approaches, the special features of arid areas, and the consequent modelling challenges.

## 1.2 RAINFALL-RUNOFF MODELLING

The book presupposes a basic understanding of modelling, and for those requiring more introductory material, the text book by Beven (2000) provides an excellent introduction, and several

*Hydrological Modeling in Arid and Semi-Arid Areas,* ed. Howard Wheater, Soroosh Sorooshian, and K. D. Sharma. Published by Cambridge University Press.

recent advanced texts are also available (e.g., Wagener *et al.*, 2004; Duan *et al.*, 2003; Singh and Frevert, 2002a,b.). Nevertheless a brief introduction to modelling terminology and issues is included here, to provide a common framework for subsequent discussion.

A model is a *simplified* representation of a real-world system, and consists of a set of simultaneous equations or a logical set of operations contained within a computer program. Models have *parameters*, which are numerical measures of a property or characteristics that are constant under specified conditions. A *lumped* model is one in which the parameters, inputs, and outputs are spatially averaged and take a single value for the entire catchment. A *distributed* model is one in which parameters, inputs, and outputs vary spatially. A semi-distributed model may adopt a lumped representation for individual subcatchments. A model is *deterministic* if a set of input values will always produce exactly the same output values, and *stochastic* if, because of random components, a set of input values need not produce the same output values. An *event-based* model produces output only for specific time periods, whereas a *continuous* model produces continuous output.

The tasks for which rainfall-runoff models are used are diverse, and the scale of applications ranges from small catchments, of the order of a few hectares, to that of global models. Typical tasks for hydrological simulation models include:

- modelling existing catchments for which input–output data exist, e.g., extension of data series for flood design of water resource evaluation, operational flood forecasting, or water resource management;
- runoff estimation on ungauged basins;
- prediction of effects of catchment change, e.g., land use change, climate change;
- coupled hydrology and geochemistry, e.g., nutrients, acid rain
- coupled hydrology and meteorology, e.g., Global Climate Models

Clearly, the modelling approach adopted will, in general, depend on the required scale of the problem (space-scale and time-scale), the type of catchment, and the modelling task. Some of the tasks pose major challenges, and it is helpful to consider a basic classification of model types, after Wheater *et al.* (1993), and their strengths and weaknesses.

### 1.2.1 Metric models

At the simplest level, all that is required to reproduce the catchment-scale relationship between storm rainfall and stream response to climatic inputs, is a volumetric loss, to account for processes such as evaporation, soil moisture storage, and groundwater recharge, and a time-distribution function, to represent the various dynamic modes of catchment response. This is the basis of the unit hydrograph method, developed in the 1930s, which, in its basic form, represents the stream response to individual storm events by a non-linear loss function and linear transfer function. The simplicity of the method provides a powerful tool for data analysis. Once a set of assumptions has been adopted (separating fast and slow components of the streamflow hydrograph and allocating rainfall losses), rainfall and streamflow data can be readily analyzed, and a unique model determined.

This analytic capability has been widely used in regional analysis. In the UK, for example, the 1975 Flood Studies Report (NERC, 1975) used data from 138 UK catchments to define regression relationships between the model parameters, and storm and catchment characteristics for the rainfall loss and transfer functions. This lumped, event-based model provides the basic tool for current UK flood design, and, through the regional regression relationships, a capability to model flow on ungauged catchments (the regional relationships were updated in the 1999 Flood Estimation Handbook (Institute of Hydrology, 1999) through the replacement of manual by digital map-based characteristics).

The unit hydrograph is also widely adopted internationally in the form of the US Soil Conservation Service model, available within the US Corps of Engineers HEC1 model. For an application to flood protection in Jordan, see Al-Weshah and El-Khoury (1999). Synthetic unit hydrographs can readily be generated based on default model parameters, which is particularly helpful in data-scarce situations. However, relatively little work has been done to evaluate the associated uncertainty with these estimates.

This data-based approach to hydrological modelling has been defined as metric modelling (Wheater *et al.*, 1993). The essential characteristic of metric models is that they are based primarily on observations and seek to characterise system response from those data. In principle, such models are limited to the range of observed data, and effects such as catchment change cannot be directly represented. In practice, the analytical power of the method has enabled some effects of change to be quantified; the UK regional analysis found the degree of urban development to be an important explanatory variable, and this is used in design to mitigate impacts of urbanization.

The unit hydrograph is a simple, event, model with limited performance capability. However methods of time-series analysis can be used to identify more complex model structures for event or continuous simulation. These are typically based on parallel linear stores, and provide a capability to represent both fast- and slow-flow components of a streamflow hydrograph (see for example Chapter 4 by Croke and Jakeman). These provide a powerful set of tools for use, with updating techniques, in real-time flood forecasting (see Chapter 9 by Young).

### 1.2.2 Conceptual models

The most common class of hydrological model in general application incorporates prior information in the form of a conceptual representation of the processes perceived to be important. The model form originated in the 1960s, when computing power allowed, for the first time, integrated representation of the terrestrial phase of the hydrological cycle, albeit using simplified relationships, to generate continuous flow sequences. These conceptual models are characterized by parameters that usually have no direct, physically measurable identity. The Stanford Watershed Model (Crawford and Linsley, 1966) is one of the earliest examples, and, with some 16–24 parameters, one of the more complex. To apply these models to a particular catchment, the model must be calibrated, i.e., fitted to an observed data set to obtain an appropriate set of parameter values, using either a manual or automatic procedure. Many of the models presented in the workshop (e.g., by Hughes (Chapter 3), Sharma (Chapter 6), Leavesley *et al.* (Chapter 7), and Wheater *et al.* (Chapter 8)) fall into this category.

The problem arises with this type of model that the information content of the available data is limited, particularly if a single performance criterion (objective function) is used (see Kleissen *et al.* 1990) and hence in calibration the problem of non-identifiability arises, defined by Beven (1993) as "equifinality." For a given model, many combinations of parameter values may give similar performance (for a given performance criterion), as indeed may different model structures. This has given rise to two major limitations. If parameters cannot be uniquely identified, then they cannot be linked to catchment characteristics, and there is a major problem in application to ungauged catchments. Similarly, it is difficult to represent catchment change if the physical significance of parameters is ambiguous.

Developments in computing power, linked to an improved understanding of modelling limitations, have led to some important theoretical and practical developments for conceptual modelling. Firstly, recognizing the problem of parameter ambiguity, appropriate methods to analyze and represent this have been developed. The concept of generalized sensitivity analysis was introduced (Spear and Hornberger, 1980), in which the search for a unique best fit parameter set for a given data set is abandoned; parameter sets are classified as either "behavioral" (consistent with the observed data) or "non-behavioral" according to a defined performance criterion. An extension of this is the generalized likelihood uncertainty estimation (GLUE) procedure (Beven and Binley, 1992; Freer *et al.*, 1996). Using Monte Carlo simulation, parameter values are sampled from the feasible parameter space (conditioned on prior information, as available). Based on a performance criterion, a "likelihood" measure can be evaluated for each simulation. Non-behavioral simulations can be rejected (based on a pre-selected threshold value), and the remainder assigned rescaled likelihood values. The outputs from the runs can then be weighted and ranked to form a cumulative distribution of output time-series, which can be used to represent the modelling uncertainty. This formal representation of uncertainty is an important development in hydrological modelling practice, although it should be noted that the GLUE procedure lumps together various forms of uncertainty, including data error, model structural uncertainty and parameter uncertainty. More generally, Monte Carlo analysis provides a powerful set of methods for evaluating model structure, parameter identifiability, and uncertainty. For example, in a recent refinement (Wagener *et al.*, 2003a,b), parameter identifiability is evaluated using a moving window to step through the output time-series, thus giving insight into the variability of model performance with time.

A second development is a recognition that much more information is available within an observed flow time-series than is indicated by a single performance criterion, and that different segments of the data contain information of particular relevance to different modes of model performance (Wheater *et al.*, 1986). This has long been recognised in manual model calibration, but has only recently been used in automatic methods. A formal methodology for multi-criterion optimization has been developed for rainfall-runoff modelling (e.g., Gupta *et al.*, 1998; Wagener *et al.*, 2000, 2002). Provision of this additional information reduces the problem of equifinality (although the extent to which this can be achieved is an open research issue), and provides new insights into model performance. For example, if one parameter set is appropriate to maximize peak flow performance, and a different set to maximize low flow performance, this may indicate model structural error, or in particular that different models apply in different ranges. Modelling tool-kits for model building and Monte Carlo analysis are currently available, which include GLUE and other associated tools for analysis of model structure, parameter identifiability, and prediction uncertainty (Lees and Wagener, 1999; Wagener *et al.*, 1999).

An important reason for detailed analysis of model structure and parameter identifiability is to explore the trade-off between identifiability and performance to produce an optimum model (or set of models) for a particular application. Thus for regionalization, the focus would be on maximizing identifiability (i.e., minimizing parameter uncertainty), so that parameters can be related to catchment characteristics.

In several senses, therefore, current approaches to parsimoneous conceptual modelling represent an extension of the metric concept (and have thus been termed hybrid metric–conceptual models). There has been a progressive recognition that the 1960s first-generation conceptual models, while seeking a comprehensive and integrated representation of the component processes, are non-identifiable. The current generation of stochastic analysis tools allows detailed investigation of model structure and parameter uncertainty, leading to parameter-efficient models that seek to extract the maximum information from the available data. They also allow formal recognition of uncertainty in model parameters, and provide the capability to produce confidence limits on model simulations.

### 1.2.3 Physics-based modelling

An alternative approach to hydrological modelling is to seek to develop "physics-based models," i.e., models explicitly based on the best available understanding of the physics of hydrological processes. Such models are based on a continuum representation of catchment processes and the equations of motion of the constituent processes are solved numerically using a grid, of course discretized relatively crudely in catchment-scale applications. They first became feasible in the 1970s when computing power became sufficient to solve the relevant coupled partial differential equations (Freeze and Harlan, 1969; Freeze, 1972). The models are thus characterized by parameters that are, in principle, measurable and have a direct physical significance. An important theoretical advantage is that if the physical parameters can be determined a priori, such models can be applied to ungauged catchments, and the effects of catchment change can be explicitly represented. However, whether this theoretical advantage is achievable in practice is an open question at present.

One of the best known models is the *Système Hydrologique Européen* (SHE) model (Abbott *et al*., 1986a,b), originally developed as a multi-national European research collaboration. In the UK this has been the subject of progressive development by the University of Newcastle-upon-Tyne, and is known as the SHETRAN model (now including TRANsport of solutes and sediments). A recent description is reported by Ewen *et al*. (2000). The catchment is discretized on a grid square basis for the representation of land surface and subsurface processes, creating a column of finite difference cells, which interact with cells from adjacent columns to represent lateral flow and transport. River networks are modelled as networks of stream links, with flow again represented by finite difference solutions of the governing equations. The resulting model is complex, computationally demanding and data intensive. Ewen *et al*. (2000) note that a one-year simulation typically has a two hour run time on an advanced UNIX system.

In practice two fundamental problems arise with such models. The underlying physics has been (necessarily) derived from small-scale, mainly laboratory-based, process observations. Hence, firstly, the processes may not apply under field conditions and at field-scales of interest. There is, for example, numerical evidence that the effects of small-scale heterogeneity may not be captured by effective, spatially aggregated, properties (Binley and Beven, 1989). Secondly, although the parameters may be measurable at small-scale, they may not be measurable at the scales of interest for application. An obvious example of both is the representation of soil water flow at hillslope-scale. Field soils are characterized by great heterogeneity and complexity. Macropore flow is ubiquitous, yet neglected in physics-based models, for lack of relevant theory and supporting data; the Richards' equation commonly used for unsaturated flow depends on strongly non-linear functional relationships to represent physical properties, for which there is no measurement basis at the spatial-scales of practical modelling interest. And field studies such as those of Pilgrim *et al*. (1978) demonstrate that the dominant modes of process response cannot be specified a priori. For more detailed discussion see, for example, Beven (1989).

There is, therefore, a need for fundamental research to address issues such as the appropriate process representation and parameterization at a given scale. For groundwater flow and transport, significant progress has been made; new theoretical approaches to the representation of heterogeneity have been developed (Dagan, 1986), and stochastic numerical methods have been developed to represent explicitly the uncertainty associated with heterogeneous properties (e.g., Wheater *et al*., 2000) and to incorporate conditioning on field observations. Extension to the more complex problems of field-scale hydrology is urgently needed, but severely constrained by data availability.

Most of the complexity of physically based models, and the associated problems discussed above, arise from the representation of subsurface flows, and the inherent lack of observability of subsurface properties. The situation often met in arid areas is that overland flow is the dominant runoff mechanism, and surface properties are, in principle, much more readily obtained. It was therefore argued by Woolhiser 30 years ago (Woolhiser, 1971), that it is in this environment that physics-based models are most likely to be successful. The well-known KINEROS model is an outstanding example, and is presented in its latest form in Chapter 5 by Semmens *et al*.

## 1.3 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

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Table 1.1 *Summary of Muscat rainfall data (1893–1959)*[a]

| 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 record | 63.0 | 64 | 62 | 63 | 61 | 61 | 60 | 61 | 61 | 60 | 61 | 60 |

[a] After Wheater and Bell, 1983

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, 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.

### 1.3.1 Rainfall

Rainfall is the primary hydrological input, but rainfall in arid and semi-arid areas is commonly characterized 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 1.1 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 the South West 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 one per 2 km$^2$. This has shown highly localized 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 (one per 20 km$^2$), representing a typical density of flash flood warning system, gave errors in simulated peak runoff of 58 %. Evidently there are major implications for hydrological practice, and 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 (FAO, 1981), but data from south-west 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 (Fig. 1.1), three draining to the Red Sea, two to the interior, towards the Rub al Khali. The mountains have elevations of up to 3000 m asl, hence the basins encompass a wide range of altitude, which is matched by a marked gradient in annual rainfall, from 30 to 100 mm on the Red Sea coastal plain to up to 450 mm at elevations in excess of 2000 m asl.

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

 

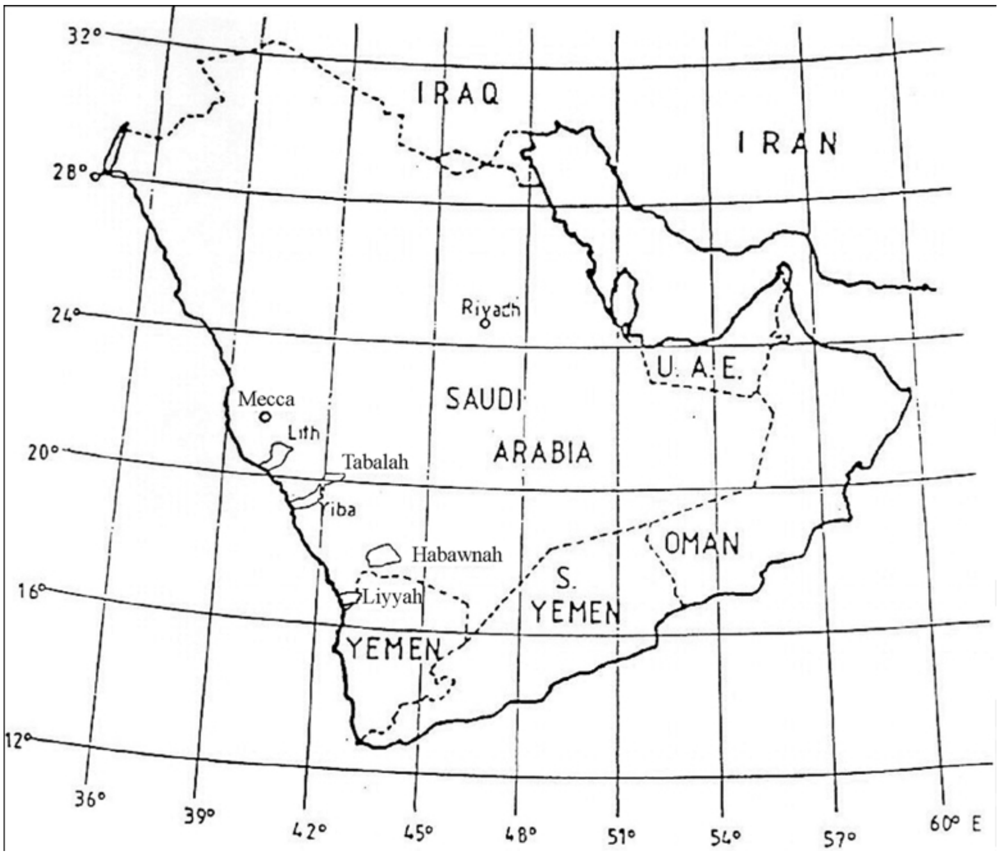


**Figure 1.1** Location of Saudi Arabian study basins

of gauges at which rainfall was observed given the occurrence of a catchment rainday (Table 1.2). Typical inter-gauge 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 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-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 Fig. 1.2, which shows the daily rainfall totals for the storm of May 16 1984 (Fig. 1.2a), and the individual hourly depths (Figs. 1.2b–1.2e). In general, the storm patterns appear to be consistent with the results from the south-west 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 a recent analysis of rainfall in Yemen (UNDP, 1992), in which it was concluded that daily rainfalls observed at any location are effectively samples from a population that is independent of position or altitude.

It is dangerous to generalize from samples of limited record length, but it is clear that most events observed by those networks are characterized 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 wide-spread 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 characterize 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

Table 1.2 *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 |

(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. Of total seasonal rainfall, 80 % was found to fall as widespread events which covered at least 70 % of the network. The number of gauges allowed the authors to analyze 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 north-east Botswana. Here, annual rainfall is of the order of

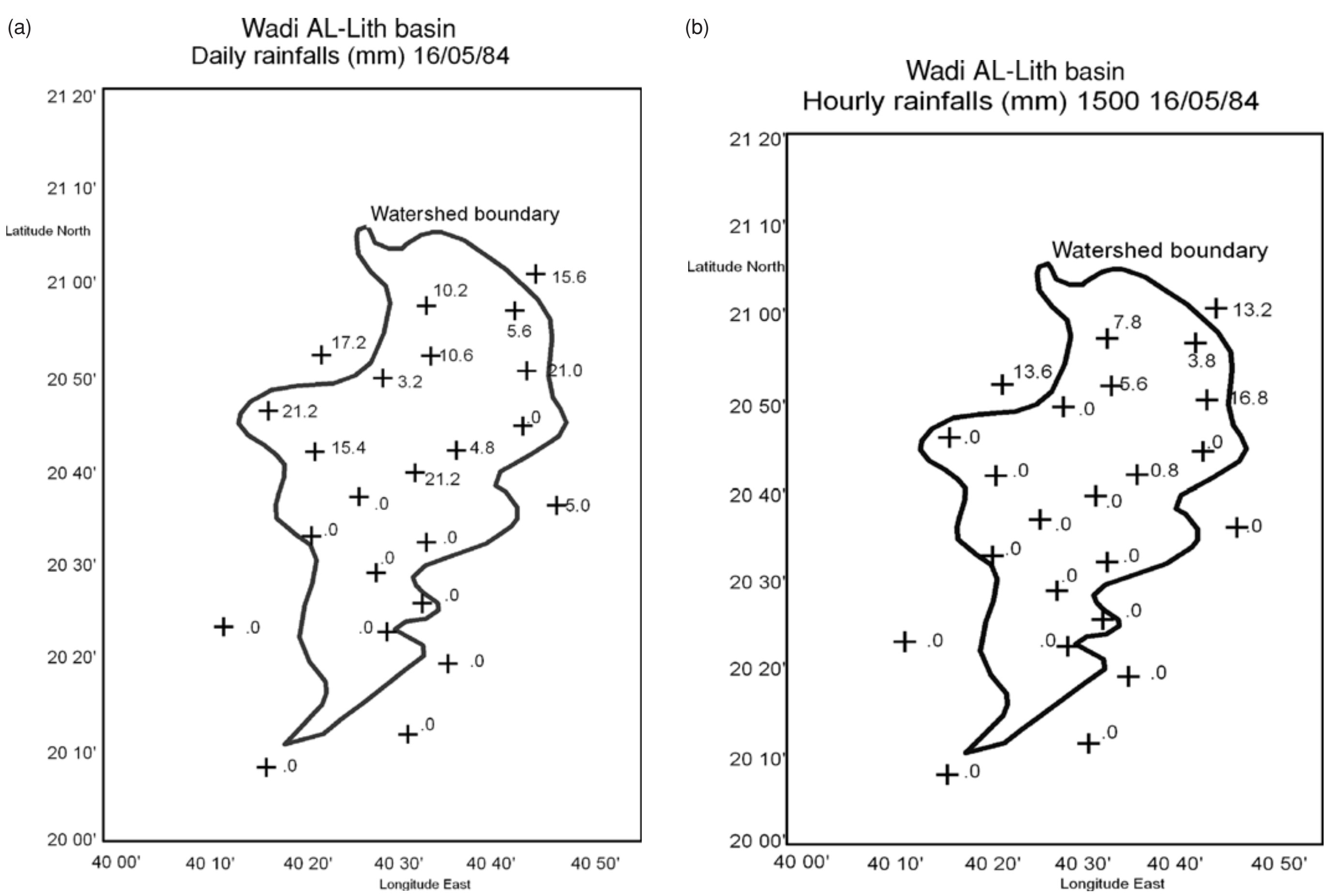


**Figure 1.2** (a)–(e) Spatial distribution of daily and hourly rainfall, Wadi Al-Lith

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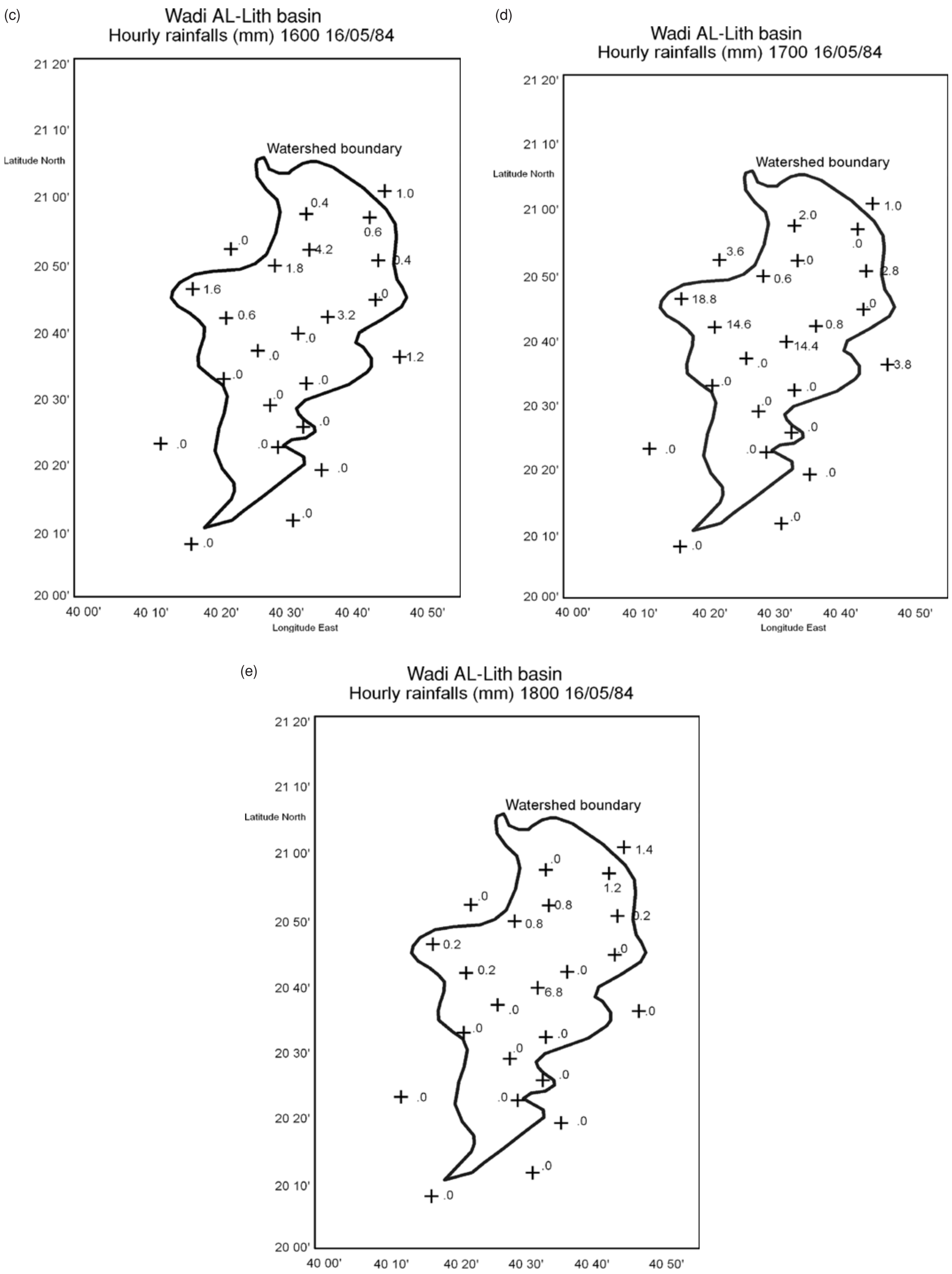


**Figure 1.2** (*cont.*)

600 mm, and available rainfall data are 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 convential methods of spatial weighting of raingauge data, such as Theissen polygons, could give large errors. Large subareas 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.

### 1.3.2 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 localized 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 is either initially dry or has a small initial flow. Hydrographs are typically characterized by extremely rapid rise times, of as little as 15–30 minutes (Fig. 1.3). 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 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 (Fig. 1.4). 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.

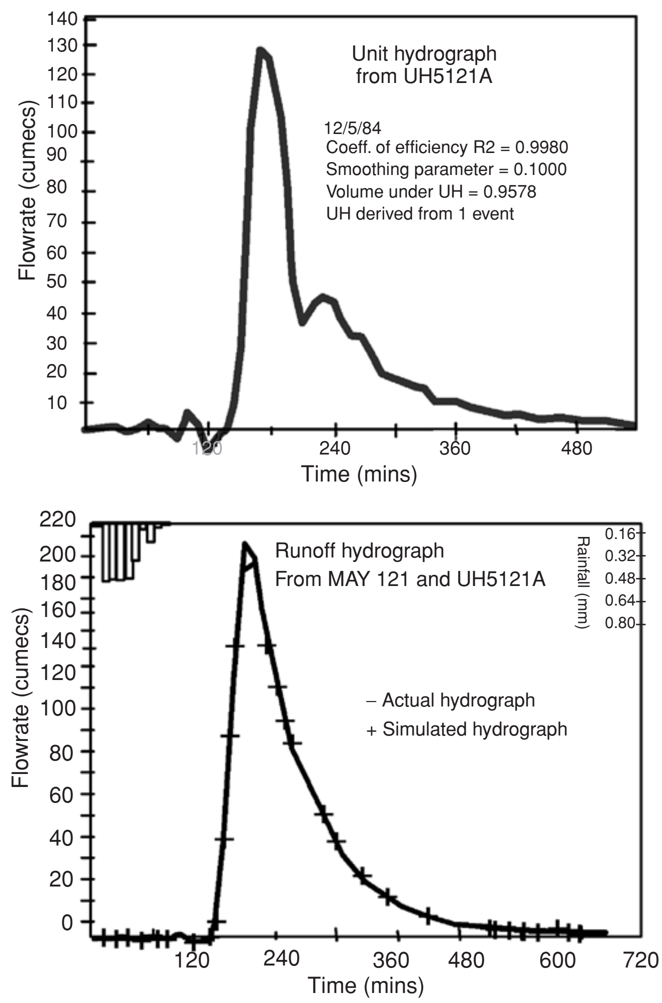


**Figure 1.3** Surface water hydrographs, Wadi Ghat May 12, 1984: observed hydrograph and unit hydrograph simulation

The transmission losses from the surface water system are a major source of potential groundwater recharge. The characteristics of the resulting groundwater resource will depend on the underlying geology, but bed infiltration may generate shallow water tables, within a few metres of the surface, which can sustain

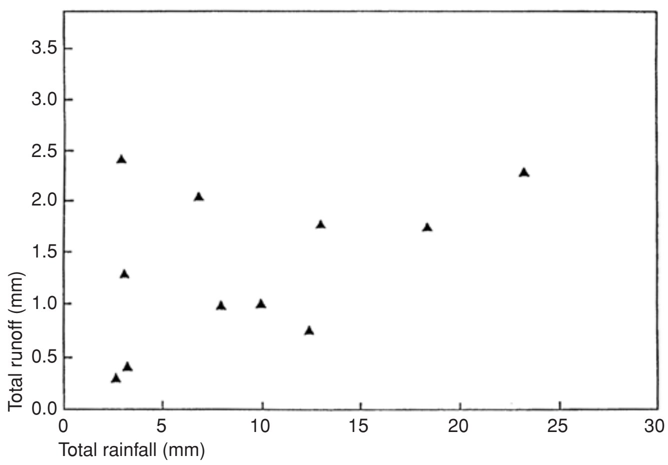


**Figure 1.4** Storm runoff as a function of rainfall, Wadi Ghat

supplies to nomadic people for a few months (as in the Hesse of the north of South Yemen), or recharge substantial alluvial aquifers with potential for continuous supply of major towns (as in northern Oman and south-west Saudi Arabia).

The balance between localized recharge from bed infiltration and diffuse recharge from rainfall infiltration of catchment soils will vary greatly depending on local circumstances. However, soil moisture data from Saudi Arabia (Macmillan, 1987) and Arizona (Liu *et al*., 1995), for example, show that most of the rainfall falling on soils in arid areas is subsequently lost by evaporation. Methods such as the chloride profile method (e.g., Bromley *et al*., 1997) and isotopic analyses (Allison and Hughes, 1978) have been used to quantify the residual percolation to groundwater in arid and semi-arid areas.

In some circumstances runoff occurs within an internal drainage basin, and fine deposits can support widespread surface ponding. A well-known large-scale example is the Azraq Oasis in north-east Jordan, but small-scale features (Qaas) are widespread in that area. Small-scale examples were found in the HAPEX-Sahel study (Desconnets *et al*., 1997). Infiltration from these areas is, in general, not well understood, but may be extremely important for aquifer recharge. Desconnets *et al.* report aquifer recharge of between 5 and 20 % of basin precipitation for valley bottom pools, depending on the distribution of annual rainfall.

The characteristics of the channel bed infiltration process are discussed in the following section. However, it is clear that the surface hydrology generating this recharge is complex and extremely difficult to quantify using conventional methods of analysis.

### 1.3.3 Wadi-bed transmission losses

Wadi bed infiltration has an important effect on flood propagation, but also provides recharge to alluvial aquifers. The balance between distributed infiltration from rainfall and wadi-bed infiltration is obviously dependant on local conditions, but soil moisture observations from south-west Saudi Arabia imply that, at least for frequent events, distributed infiltration of catchment soils is limited, and that increased near-surface soil moisture levels are subsequently depleted by evaporation. Hence wadi-bed infiltration may be the dominant process of groundwater recharge. As noted above, depending on the local hydrogeology, alluvial groundwater may be a readily accessible water resource. Quantification of transmission loss is thus important, but raises a number of difficulties.

One method of determining the hydraulic properties of the wadi alluvium is to undertake infiltration tests. Infiltrometer experiments give an indication of the saturated hydraulic conductivity of the surface. However, if an infiltration experiment is combined with measurement of the vertical distribution of moisture content, for example using a neutron probe, inverse solution of a numerical model of unsaturated flow can be used to identify the unsaturated hydraulic conductivity relationships and moisture characteristic curves. This is illustrated for the Saudi Arabian Five Basins Study by Parissopoulos and Wheater (1992a).

In practice, spatial heterogeneity will introduce major difficulties to the up-scaling of point profile measurements. The presence of silt lenses within the alluvium was shown to have important effects on surface infiltration as well as subsurface redistribution (Parissopoulos and Wheater, 1990), and subsurface heterogeneity is difficult and expensive to characterize. In a series of two-dimensional numerical experiments it was shown that "infiltration opportunity time," i.e., the duration and spatial extent of surface wetting, was more important than high flow stage in influencing infiltration, that significant reductions in infiltration occured once hydraulic connection was made with a water table, and that hysteresis effects were generally small (Parissopoulos and Wheater, 1992b). Also sands and gravels appeared effective in restricting evaporation losses from groundwater (Parissopoulos and Wheater, 1991).

Additional process complexity arises, however. General experience from the Five Basins Study was that wadi alluvium was highly transmissive, yet observed flood propagation indicated significantly lower losses than could be inferred from *in situ* hydraulic properties, even allowing for subsurface heterogeneity. Possible causes are air entrapment, which could restrict infiltration rates, and the unknown effects of bed mobilization and possible pore blockage by the heavy sediment loads transmitted under flood flow conditions.

A commonly observed effect is that in the recession phase of the flow, deposition of a thin (1–2 mm) skin of fine sediment on the wadi bed occurs, which is sufficient to sustain flow over an unsaturated and transmissive wadi bed. Once the flow has ceased, this skin dries and breaks up so that the underlying alluvium is exposed for subsequent flow events. Crerar *et al*. (1988) observed from