An integrated model of arid zone water resources: evaluation of rainfall-runoff simulation performance

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Abstract The structure of an integrated modelling procedure for arid zone water resources management is outlined, based on the need for evaluation of groundwater recharge management options. The daily time step rainfall-runoff component was evaluated using data from the USDA ARS experimental basin at Walnut Gulch, Arizona. Interdependence between the parameters defining runoff production and channel bed transmission loss was resolved by detailed analysis of reach-scale transmission losses, and model calibration incorporated the effects of antecedent precipitation on runoff production. Simulation results were encouraging, and the existence of well defined relationships between flood volume and flood peak allows potential model application to include flood peak estimation. The need for integrated surface and subsurface monitoring is emphasized, as are the outstanding problems of rainfall representation for arid areas.

INTRODUCTION

As populations grow and economic activity increases, there is increasing demand for scarce water resources in arid and semiarid regions. This focuses attention on maximizing the development of renewable water resources. It is therefore essential to develop modelling techniques which can represent the dominant hydrological processes and their temporal variability, so that management options can be explored and long term sustainability investigated.

The hydrology of arid and semiarid areas is substantially different from that of humid regions and, historically, data from arid regions have 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; Némec & Rodier, 1979; Pilgrim et al., 1988). As a result, the unique characteristics of the hydrological response of arid areas have not been fully understood and hence the techniques commonly used in hydrological design and water resources management have generally been borrowed from the humid zone with little question (Wheater, 1994).

In recent years there have been important developments in data availability, however. A decade ago, the primary sources of detailed information on arid zone catchments available in the published literature remained the two, relatively small, experimental basins in southwest USA: Walnut Gulch in Arizona and Alamogordo Creek in New Mexico (150 and 174 km², respectively) (Osborn et al., 1979). However, the pro-
gressive development of regional data bases in the Middle East and elsewhere has been accompanied by a number of more detailed studies (e.g. Saudi Arabian Dames and Moore, 1988). This has led to improved understanding of the characteristics and importance of spatial rainfall in that region (e.g. Wheater et al., 1991a, 1991b), the controls on groundwater recharge of alluvial aquifers from ephemeral surface flows (Parissopoulos & Wheater, 1990, 1991, 1992a, 1992b; Walters, 1990; Sorman & Abdulrazzak, 1993), and the limitations of conventional rainfall-runoff analysis applied to arid areas (Wheater & Brown, 1989).

On the basis of this improved understanding, an integrated modelling procedure was recently developed for the evaluation of options for recharge management in Wadi Ghulaji, northern Oman (Wheater et al., 1995), although based on limited calibration data. In this paper, the structure of the integrated modelling procedure is described, and detailed assessment of one component, the rainfall-runoff model, is presented, based on data from the intensively monitored Walnut Gulch catchment in Arizona.

HYDROLOGICAL PROCESSES IN ARID AREAS

The highly localized nature of convective flood producing rainfall in many arid areas has long been recognized as a key factor in determining catchment-scale response (FAO, 1981; Wheater, 1994). This is clearly demonstrated in early results from the Walnut Gulch raingauge network (Osborn et al., 1979) and reinforced by data from Saudi Arabia (Wheater et al., 1991a, 1991b) and elsewhere. Localized, intense rainfall of short duration falling on soils with limited vegetative cover generates Hortonian excess overland flow, enhanced by surface crusting (Morin & Benyamini, 1977). Overland flow is rapidly transmitted to an ephemeral stream system to generate a flood flow. Flood hydrographs commonly have an extremely short rise time (15-30 min), and the floods move downstream as a discrete wave front, the so-called "wall of water", or as a series of waves, over a dry alluvial channel. Hydrograph volumes generally decrease with distance downstream due to bed infiltration, i.e. a transmission loss. Depending on the hydrogeological characteristics of the alluvium, the transmission loss can provide a major source of recharge to the underlying aquifer.

Such alluvial groundwater systems can provide continuous yields for water supply to towns and villages, or, where alluvium depths are limited, simply a local source of water for nomadic herdsmen for a period of a few weeks or months. In recent years there has been considerable interest, most notably in the Sultanate of Oman, in active management of such alluvial systems. The construction of flood detention structures can slow the transmission of the flood and lead to the focusing of recharge on particular locations. This can increase groundwater resources, for example, as in the Batinah plain of northern Oman, by preventing loss of flood water to the sea, or, as in the interior of Oman, loss to inaccessible groundwater in the Rub al Khali or Empty Quarter.

It can readily be appreciated that to consider water resource management options, an integrated approach to the representation of surface water and groundwater is required. In addition, distributed modelling is essential to capture the spatial variability of the process response (Michaud & Sorooshian, 1994a), as well as to investigate management options at different locations.
THE INTEGRATED MODELLING STRATEGY

The structure of the integrated modelling strategy developed for northern Oman is shown in Fig. 1. A distributed rainfall model, based at present on a simple multivariate model of raingauge rainfall, developed from Wheater et al. (1991a), is used to provide stochastic input sequences of daily rainfall to the rainfall-runoff model. The rainfall-runoff model conceptualizes the catchment as a network of planes and channels, with discrimination between jebel (hill slope) and alluvial planes. The model includes a number of options to represent runoff from the plane elements, including the US Soil Conservation Service (SCS) method (US SCS, 1968; McCuen, 1982).

The channels are represented as a series of one-dimensional elements and transmission loss is represented as a linear function of upstream discharge, following Jordan (1977), i.e.:

$$\frac{dV_x}{dx} = -KV_x$$

where $x = $ distance downstream; $V_x = $ flow volume at location $x$; and $K = $ constant of proportionality, which can be expressed as:

$$V_x = V_A(1 - \alpha)^x$$

where $V_A$ is the flow volume at $A (x = 0)$ and $\alpha$ represents the proportion of flow lost per unit distance for a given channel element.

Fig. 1 Schematic of the integrated modelling procedure.
Transmission loss provides groundwater recharge to a distributed multi-layer groundwater flow model (MODFLOW).

The parameters of the rainfall-runoff model are thus the SCS curve number (CN) and the transmission loss parameter \( \alpha \). It is evident that strong dependence can be expected between these two in calibration using flow data alone, since similar results can be expected from a high curve number and high transmission loss parameter as from low CN and \( \alpha \). Additional constraints can be provided by groundwater data, or, as discussed below, by additional information on surface response.

THE WALNUT GULCH EXPERIMENTAL BASIN

The US Department of Agriculture Agricultural Research Service established the 150 m\(^2\) Walnut Gulch watershed as an experimental basin in 1953. The basin is located in southeast Arizona, near to Tucson. The original rainfall monitoring network was progressively developed so that by 1967 there was a network of 95 weighing type recording raingauges. Runoff is measured at the basin outlet and from 25 sub-basins by a combination of permanent structures and water level recorders (Gwinn, 1964; Osborn et al., 1963; Osborn & Renard, 1970). For this study, the catchment was split into 11 sub-basins (all gauged) (Fig. 2 and Table 1).

Elevations range from 1200 to 1800 m, and the basin consists of gently rolling rangeland, mostly underlain by Quaternary basin fill, although bedrock underlies the rocky hills in the southwest of the basin. Vegetation is dominated by native shrubs and grasses and there is no cultivation, only some cattle grazing. Major channels have steep slopes (approximately 1\%). Channel beds generally comprise 1 m or more of unconsolidated sand and gravel overlying bedrock or fine textured sediment (Renard & Keppell, 1966). The small town of Tombstone is located in the lower part of the catchment.

Most of the rainfall derives from multi-cellular convective thunderstorms of high intensity, short duration and limited areal extent, and a strong diurnal pattern exists, with approximately 80\% of storms occurring between 1200 and 2200 h. There seems to be general similarity between the patterns of rainfall here and for convective rainfall in Arabia (Wheater et al., 1991a). Wheater et al. (1989) note general similarities in areal reduction factors between southwest Saudi Arabia and southwest USA, for example. The intense, short duration rainfall and steep channels promote rapid hydrograph response, sharp hydrograph peaks, and relatively short duration flows (Renard & Keppell, 1966).

TRANSMISSION LOSS

The processes of transmission loss are complex, and not fully understood. Infiltration experiments can be carried out in wadi alluvium to determine hydraulic properties (e.g. Parissopoulos & Wheater, 1992a), and may show highly transmissive profiles. In practice, spatial heterogeneity is likely to introduce considerable complexity to the infiltration process and to up-scaling from point properties. Parissopoulos & Wheater (1990) illustrate this using two-dimensional simulation and also show that significant
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Fig. 2. The Walnut Gulch experimental basin: location of reaches 11-8 and 6-2.
reductions in infiltration rates occur once hydraulic connection is established with an underlying water table. Over and above these effects, however, are the influences of air entrapment and sedimentation, which are largely unknown. Hence reach-scale studies (e.g. Walters, 1990; Jordan, 1977) are essential to quantify loss response.

As noted above, calibration of the two-parameter rainfall-runoff model has the problem of interderminancy resulting from strong parameter interdependence. In the Oman application, groundwater response was used to constrain parameters. Here, groundwater data are not available, but the relatively high density of flow gauges means that direct analysis of transmission loss is possible. Two stretches of channel were identified for detailed analysis (Fig. 2):

(a) 6.60 km between flume 11 and flume 8; and
(b) 4.51 km between flume 6 and flume 2.

Events were selected from a ten-year sequence (1968-1977) for which no tributary inflows were apparent and flow had been observed at both upstream and downstream locations. Combined results showing the loss parameter $\alpha$ as a function of upstream discharge are presented in Fig. 3 for the two individual reaches. It is apparent that $\alpha$ is not a unique parameter for these locations, but is strongly dependent on upstream discharge. However, a consistent relationship was apparent for both locations. This
relationship could not be improved by consideration of antecedent conditions in the channel (Woods Ballard, 1996).

The reduction in $\alpha$ with upstream storm volume may reflect the relatively limited alluvial depths in the catchment. For example, a temporary hydraulic connection with an underlying water table may occur during sustained flood events. Lane et al. (1971) suggest, based on bed properties, that there is a maximum holding capacity in the reach between flumes 8 and 11 in the approximate range 4800-6700 m$^3$ km$^{-1}$. The average loss per km for the events considered here has a maximum value of 4076 m$^3$ km$^{-1}$.

It should be noted that Jordan’s relationship was found to be improved if channel width is included (Walters, 1990; Sorman & Abdulrazzak, 1993), and that in the Oman application (Wheater et al., 1995), $\alpha$ was increased downstream to allow for effects of increased wadi widths. The analysis here shows consistency for the two reaches investigated but these were of similar lengths and channel form.

**DISTRIBUTED MODELLING OF THE RAINFALL-RUNOFF PROCESS**

The rainfall-runoff model was setup, using a GIS system to configure the discretization into planes and channel segments, to represent the catchment area to Tombstone, i.e. including 9 of the 11 sub-areas of Fig. 2. The original model was applied with constant $\alpha$, and the SCS option for runoff generation was applied, using a single value of curve number, $CN$, for each sub-basin. The two parameters were calibrated for each sub-basin for a set of six events (Table 2). The expected dependence of $\alpha$ and $CN$ was observed. Calibration performance was variable, and split-sample performance on a further set of three events was poor.

Following the transmission loss analysis of the two reaches discussed above, the model was modified to incorporate the observed relationship between transmission loss and upstream discharge, i.e.:

$$\alpha = 118.80 (V_A)^{0.71}$$

subject to the constraint $\alpha > 1$. No spatial variability in $\alpha$ was considered at this stage.

As noted above, the model includes the US SCS algorithm for runoff generation.

**Table 2** Calibration and validation performance, original and improved models.

<table>
<thead>
<tr>
<th>Sub-basin</th>
<th>Objective error function ($R^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Original model</td>
</tr>
<tr>
<td></td>
<td>Calibration</td>
</tr>
<tr>
<td>2</td>
<td>0.88</td>
</tr>
<tr>
<td>3</td>
<td>0.94</td>
</tr>
<tr>
<td>4</td>
<td>0.63</td>
</tr>
<tr>
<td>5</td>
<td>0.71</td>
</tr>
<tr>
<td>6</td>
<td>0.94</td>
</tr>
<tr>
<td>8</td>
<td>0.22</td>
</tr>
<tr>
<td>9</td>
<td>0.73</td>
</tr>
<tr>
<td>10</td>
<td>-0.48</td>
</tr>
<tr>
<td>11</td>
<td>0.35</td>
</tr>
</tbody>
</table>
The SCS procedure allows for some simple curve number modification according to season and 5 day antecedent precipitation. Based on inspection of limited soil moisture observations from Walnut Gulch (Woods Ballard, 1996), this concept was extended here to a six class antecedent precipitation index based on the number of dry days prior to an event, with an enhancement for prior heavy rainfall (Table 3). Two land use types were used, one for steeper grassland sub-basins, another for shallower, shrubland sub-basins, and a limited calibration exercise was undertaken on a calibration set of six events to produce the rules of Table 4.

Table 3 Definition of antecedent precipitation index.

<table>
<thead>
<tr>
<th>Index</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of dry days prior to the event</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>Heavy rainfall for some time</td>
</tr>
</tbody>
</table>

Table 4 Curve numbers as a function of land use and antecedent conditions.

<table>
<thead>
<tr>
<th>API</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>CN for steeper, grassland sub-basins (3, 4, 8, 9, 10, 11)</td>
<td>85</td>
<td>81</td>
<td>78</td>
<td>75</td>
<td>73</td>
<td>71</td>
<td>88</td>
</tr>
<tr>
<td>CN for shallower, shrubland sub-basins (2, 5, 6)</td>
<td>80</td>
<td>78</td>
<td>75</td>
<td>73</td>
<td>71</td>
<td>68</td>
<td>85</td>
</tr>
</tbody>
</table>

The resulting optimized performance was generally improved, with a much more consistent set of results, and the split sample performance was greatly enhanced (Table 2). Performance is illustrated for sub-basins 2 and 4 in Fig. 4. Although the model produces daily hydrograph volumes, there is a highly consistent relationship for individual basins between hydrograph peak and volume, illustrated in Fig. 5. Thus simulated volumes can be used, if required, to provide peak flow estimates.

CONCLUSIONS

Detailed data to validate hydrological models of arid zone processes remain limited, and the Walnut Gulch experimental basin provides a unique test bed for surface hydrology. The rainfall-runoff component of an integrated water resource modelling procedure has been tested, and significant improvements in performance observed when a locally defined transmission loss relationship was incorporated, together with a representation for runoff production of antecedent conditions. The performance of the calibrated daily flow model was encouraging, and well defined relationships were observed between flow volumes and hydrograph peaks, so that the simulated flood volumes could be used to estimate flood peak response.

Transmission losses, and their resulting groundwater recharge, are a key issue for
water resources management in ephemeral stream systems, and due to process complexity and problems of scaling, reach-scale observations are likely to remain the main source of useful information for the immediate future. There is a major need for further observational studies worldwide to enhance the extremely limited data base for such analyses.

The issues of rainfall have not been addressed here. The high density of gauges at Walnut Gulch has proved adequate for the daily rainfall-runoff model reported here, but for most practical applications, such detailed data will not be available. Research is needed to quantify the degradation of performance associated with reduced rainfall information, although its effects have been clearly demonstrated for flood models by
Michaud & Sorooshian (1994b). The multivariate modelling approach of Wheater et al. (1995) is a first attempt to represent rainfall variability in this modelling procedure, but ideally, a full stochastic spatial-temporal rainfall is required.

Similarly, groundwater response has not been considered. It is interesting to note that despite the very high quality of surface hydrology data at Walnut Gulch, subsurface information is limited, and there is a major international need for arid zone research basins to include integrated monitoring of both surface and subsurface processes.

Acknowledgements B. Woods Ballard was in receipt of an Advanced Course Studentship from the UK Natural Environment Research Council. Data from Walnut Gulch was obtained from the USDA ARS water database with assistance from Dr L. J. Lane.

REFERENCES


