A catchment water balance model for estimating groundwater recharge in arid and semiarid regions of south-east Iran

E. Khazaei · A. E. F. Spink · James W. Warner

Abstract This paper presents a new model of the rainfall-runoff-groundwater flow processes applicable to semiarid and arid catchments in south-east Iran. The main purpose of the model is to assess the groundwater recharge to aquifers in these catchments. The model takes into account main recharge mechanisms in the region, including subsurface flow in the valley alluvium in mountainous areas and recharge from the bed of ephemeral rivers. It deals with the effects of spatial variation in the hydrological processes by dividing the catchment into regions of broad hydrologic similarity named as highland, intermediate and aquifer areas. The model is based on the concept of routing precipitation within and through the catchment. The model has been applied to the Zahedan catchment and the results indicate that the groundwater level estimated by the recharge model generally is in agreement with the behaviour of groundwater levels in observation wells. The sensitivity analysis indicates that when the rainfall in the aquifer area is used to replace the values recorded in the intermediate area and the highland area, the recharge estimates are reduced by 42-87%. This result supports the division of the catchment into different zones of hydrological similarity to account for spatial variability of hydrological processes.

Résumé Ce papier présente un nouveau modèle de processus d'écoulement pluie - ruissellement - écoulement souterrain applicable aux bassins de régions arides et semi-arides du sud-est de l'Iran. Le principal but de ce modèle est d'évaluer la recharge des nappes dans ces bassins. Le modèle prend en compte les principaux mécanismes de recharge dans cette région, qui sont les écoulements souterrains dans les alluvions des vallées en région montagneuse et la recharge dans le lit des cours d'eau temporaires. Il aborde les effets des variations spatiales des processus hydrologiques en divisant le bassin en différentes régions possédant des caractères hydrologiques assez semblables, telles que les régions de montagne, intermédiaire et aquifère. Le principe du modèle est basé sur le concept de transfert de précipitation dans et au travers du bassin. Le modèle a été appliqué au bassin de Zahedan et les résultats indiquent que le niveau de la nappe estimé par le modèle de recharge est généralement en bon accord avec le comportement général du niveau de la nappe observé dans les puits. L'analyse de sensibilité indique que lorsque la pluie de la région aquifère est utilisée à la place des valeurs enregistrées dans la région intermédiaire et la région de montagne, l'estimation de la recharge est sous-évaluée de 42 à 87%. Ce résultat justifie la division du bassin en différentes zones hydrologiques pour prendre en compte la variabilité spatiale des processus hydrologiques.

Resumen Este artículo presenta un nuevo modelo de los procesos de precipitación-escorrentía-flujo subterráneo para cuencas áridas y semiáridas del Sudeste de Irán. El objetivo del modelo es determinar la recarga a los acuíferos de esas cuencas. El modelo considera los mecanismos principales de recarga en la región, es decir, de flujo subsuperficial de los aluviales en zonas montañosas y de recarga de cursos fluviales efímeros. Trata los efectos de la variabilidad espacial en los procesos hidrológicos, para lo que divide la cuenca en tres regiones diferentes de similitud hidrológica: Tierras Altas, Intermedias y Acuíferas. El modelo se basa en el concepto de dirigir la precipitación dentro y a través de la cuenca. Se ha aplicado a la cuenca de Zahedan, y los resultados indican que los niveles piezométricos estimados con el modelo de recarga reproducen el comportamiento general de los niveles medidos en pozos de observación. El análisis de sensibilidad indica que, cuando se usa la precipitación en la superficie del acuífero para sustituir los valores registrados en la zona Intermedia y en las Tierras Altas, se obtiene una reducción en la estimación de la recarga del 42% al 87%. Este resultado confirma que la división de la cuenca en zonas de similitud hidrológica

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sirve para tener en cuenta la variabilidad espacial de los procesos hidrológicos.

Keywords Arid and semiarid regions · Catchment · Groundwater recharge · Iran · Water balance model

Introduction

Groundwater is the sole source of water supply for domestic, agriculture and industrial uses in most arid and semiarid regions of south-eastern Iran (Khazaei and Alemi 2001). The rapid growth of population (ranging between 7.5-13%, Plan and Budget Organisation branch in Zahedan, personal correspondence, 2001) and urban development in these regions creates shortages of water (Khazaei 2001). Therefore, efficient groundwater management is necessary. The quantification of groundwater recharge is a prerequisite for efficient and sustainable groundwater-resource management in arid regions (Vries and Simmers 2002). Consequently, developing methods for the accurate evaluation of recharge has great value.

Groundwater recharge is one of the most difficult components of the hydrologic budget to quantify (Stephens and Knowlton 1986; Jackson and Rushton 1987; Cook and Kilty 1992; Stone et al. 2001). There is an increased difficulty in dealing with arid regions because of the variability of recharge with respect to time and space that is characteristics of arid areas (Verma 1979; Yair and Lavee 1985; Simmers 1988). The scarcity of data due to sparse habitation, as well as the character of the climatic regime, further magnifies the problem (Lerner et al. 1990). Because of these difficulties, the estimation of groundwater recharge in arid regions has not been adequately addressed.

Natural recharge to an aquifer in an arid region may occur by various mechanisms, such as infiltration from the beds of ephemeral rivers (Moench and Kisiel 1970; Besbes et al. 1978; Abdulrazzak 1983; Dillon and Liggett 1983; Lloyd 1986; Walters 1990; Sorman and Abdulrazzak 1993), subsurface drainage from mountain areas through the alluvial material of valley beds (Khazaei 1999) and the direct entrance of rainfall into the alluvial material of the lower plains (Dincer et al. 1974). In order to develop a successful recharge estimation approach for a region, the effects of all the mechanisms must be taken into account. To achieve this objective, Miles and Rushton (1983) and Simmers (1989) recommend a total catchment water balance approach. In this method all the factors affecting the recharge in the catchment, such as precipitation, evaporation, surface runoff, interflow, groundwater inflow and outflow, are incorporated (Senarath and Rushton 1984).

A number of catchment water balance or conceptual models have been developed for the purpose of rainfall runoff simulation. Typical of these models are the Stanford watershed model (Crawford and Linsley 1966), the Monash model (Porter and McMahon 1971) and the Institute of Hydrology model (Blackie and Eeles 1985). These conceptual models are mathematical models, which consist of a set of storage elements linked by pathways for water movement (Chapman 1990). The number and definition of the storage elements depends on the nature of the problem. For each storage element, the water balance or conservation of mass equation is applied over a given time interval. Because groundwater is a component of these models, in theory they can be used for estimating the groundwater recharge. Chiew and McMahon (1990) applied the Monash model to estimate groundwater recharge in the Campaspe River Basin from Lake Eppalock to Rochester in northern Victoria, Australia. The catchment has an area of 1,415 km^2, which was divided into ten subcatchments to take into account the spatial variation of hydrological processes. The model was applied to each subcatchment starting from the upstream end. Rippon and Wyness (1994) and Pearce and Jones (1995) used the Stanford watershed model to make initial estimates of recharge in a number of catchments in the UK. Their aim was to provide an input to the integrated catchment management model, which was developed by Mott MacDonald. However, none of the authors gives information about the date of the development of the integrated catchment management model. Senarath and Rushton (1984) developed an entire catchment water balance model for the purpose of estimating groundwater recharge.

It is well known that, in arid regions, the recharge from the bed of ephemeral rivers, and subsurface flow in valley bed alluvium in mountainous areas, are important mechanisms. Furthermore, the recharge mechanisms in these regions vary greatly within the catchment due to the spatial variation of rainfall along with variation of geology and physiographic features (Verma 1979; Yair and Lavee 1985; Simmers 1988; Lerner et al. 1990). However, it appears that the Stanford watershed model, or any of the other models, does not take into account the above mechanisms as well as the spatial variability of the recharge within the catchment. Thus, the present models cannot represent the overall catchment behaviour in arid regions and, consequently, they cannot be applied successfully for recharge estimation in these regions. Consequently, a reasonable estimate of the recharge in an arid region needs a new approach, which takes into account the mechanisms, that are typical of local conditions and deals with the spatial variation of hydrological processes (Simmers 1989).

Here, a catchment water balance is developed that takes into account the main recharge mechanisms and deals with the spatial variation of the water balance components within the catchment. The model is developed using the hydrological characteristics of the Zahedan catchment (Fig. 1), which has many features that are typical of the region. In order to allow for variations in the hydrological processes, the catchment is divided into zones with similar characteristics. Furthermore, each zone is divided into a rock area and an alluvial area.

In Zahedan catchment, the rocks are composed of old flysch, igneous rocks and young flysch (Fig. 1). The old

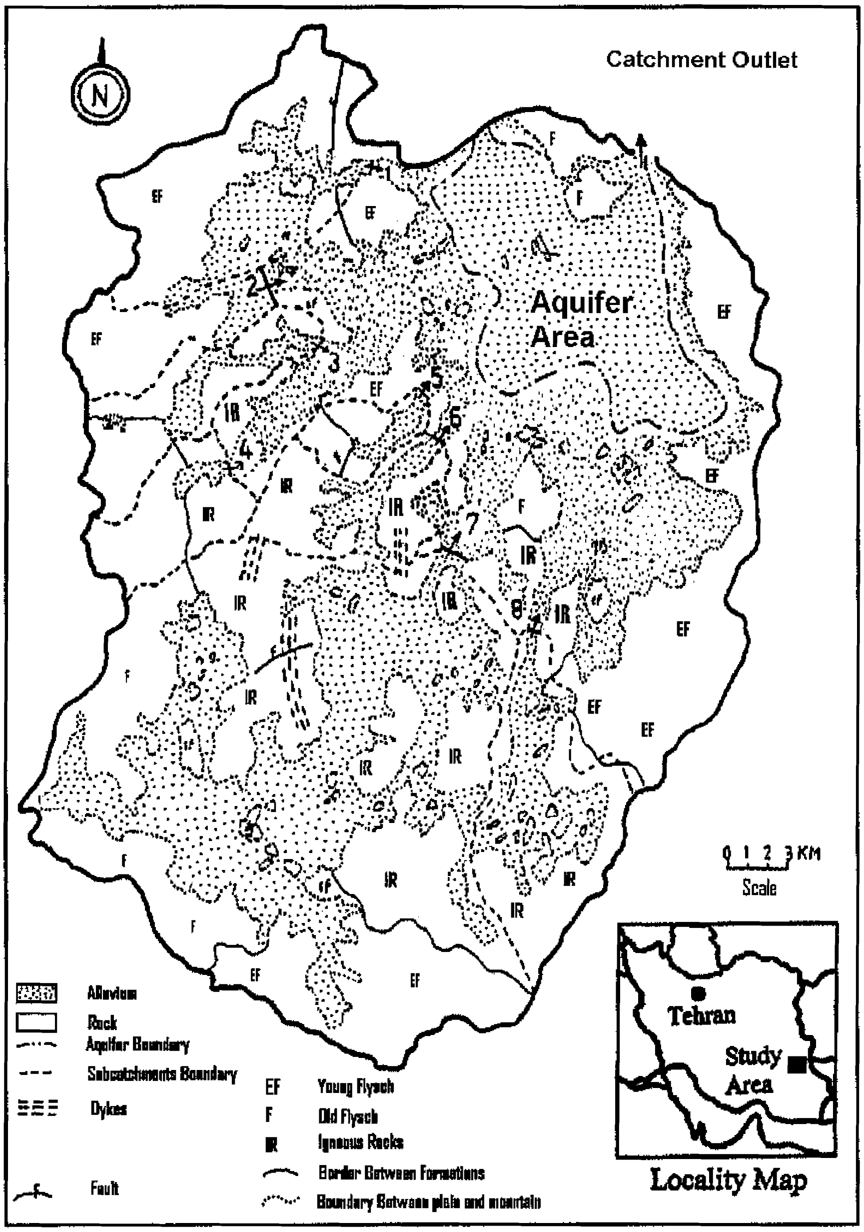

Fig. 1 The Zahedan catchment and the formation outcrops, eight subcatchments in the highland area and approximate aquifer area (modified after Bandab 1987)

flysch (upper Cretaceous and Palaeocene) consists of alternate layers of shale, sandstone, siltstone, mudstone and thin lenses of limestone. The north-west-south-east-trending mountains in the areas to the north-west, west and south are formed from granite (Eocene to Oligocene). The young flysch (middle Tertiary) seen in the western and southern parts of the catchment as hills and in the northern and eastern parts as mountains is composed of marine facies containing conglomerates with red clay cement, layers of fine-grained sandstone with clay and calcareous cement, thin layers of marl, coloured shales, mudstone and siltstone along with gypsum and halite. In general, the rock area in Zahedan catchment is impermeable (Bandab 1987).

In the Zahedan catchment, and in most of the catchments in south-east Iran, three broad regions of hydrologic similarity may be distinguished: a highland area, an area of intermediate elevation and a lower area containing the principal aquifers (Fig. 1 and 2). Each of the constituent areas is described below.

Highland Area

The highland area constitutes a large portion of the catchments in south-east Iran. It may consist of several subcatchments, which conduct surface runoff to the intermediate zone and, subsequently, to the aquifer area. According to Yair and Lavee (1985) and Lerner et al. (1990), in arid regions chemical weathering processes are negligible while erosion occurs during short rain storms as well as from wind-driven processes during dry periods. Because of this, upland regions are devoid of soil cover and have steep rocky slopes, whereas, in the valleys,

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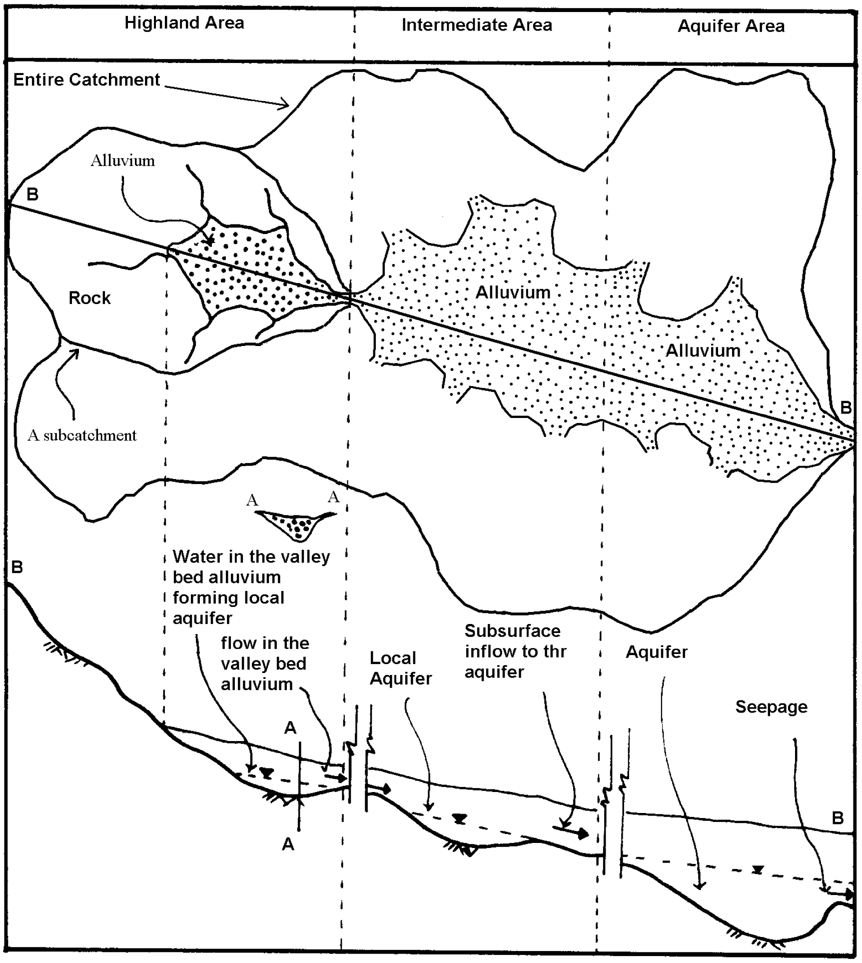

Fig. 2 Schematic diagram (plan and cross section) showing different parts within a catchment

depositional alluvial materials may be found. This situation occurs in most catchments. The type of alluvial material depends on the surrounding rocks. The area of valley bed alluvium is usually less than 30% of the area of each subcatchment (Khazaei 1997). The rocks are impermeable owing to the nature of the geology of the region (Pars Consult 1977; Bandab 1987). The bareness of the rock and steep slopes, in combination with higher precipitation and lower evaporation, cause significant surface runoff in these areas. The highland area itself is also divided into different subcatchments to overcome the effect of spatial and temporal variations. In each subcatchment in the mountainous area, a part of the rainfall, in excess of that used for immediate evaporation, wetting the land surface and filling cracks, may infiltrate into the valley bed alluvium or appear as surface runoff. The water that infiltrates into the valley bed alluvium drains into the plain as subsurface flow. Subsurface flow in alluvium laying on an impermeable valley bed is an important source of groundwater recharge to the alluvial aquifers located in the deltaic plain. Figure 3 shows a schematic diagram of the various routes that the rainfall may take in a mountainous area, including alluvial subsurface flow.

Intermediate Area

The term intermediate is used to describe the land lying between the highland area and the alluvial plain containing the main aquifer (Fig. 2). It comprises that part of the mountain that is oriented towards the plain, isolated rocky hills and some alluvium. In general, the area covered by alluvium is larger than that consisting of bare rock. The alluvial material consists of gravel, sand and silt. Lenses of clay may also be present. Small local aquifers may be formed where the configuration of the bedrock is suitable (Fig. 2).

The Aquifer Area

That part of the plain in which alluvial materials are saturated below a water table is called the aquifer area. In the aquifer area, the saturated thickness may vary owing to the undulating nature of the bedrock. Sometimes the bedrock may appear as isolated hills within the aquifer area. The presence of water permits the development of rural or urban settlements in this part of the catchment.

For each region, a water balance approach is developed by a careful study of the processes by which runoff and recharge are produced from rainfall. Routing techniques are used in order to distribute the flow along possible pathways. A daily time step is chosen because

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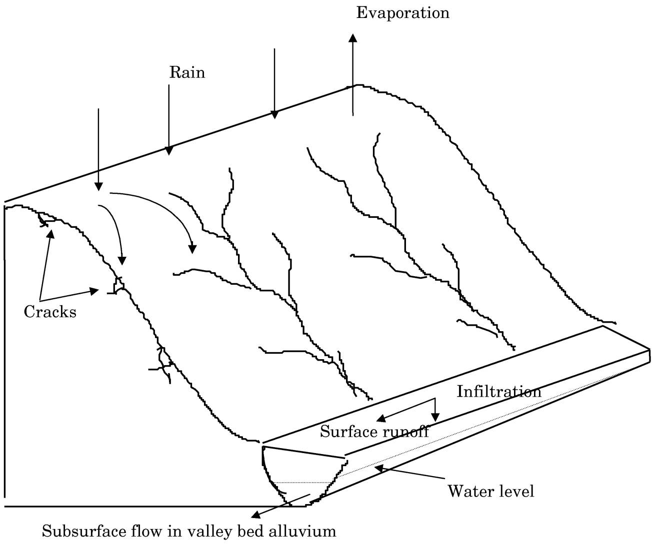


Fig. 3 Various routes that rainfall takes in the mountainous area of an arid region

there is usually insufficient data to justify a smaller time step.

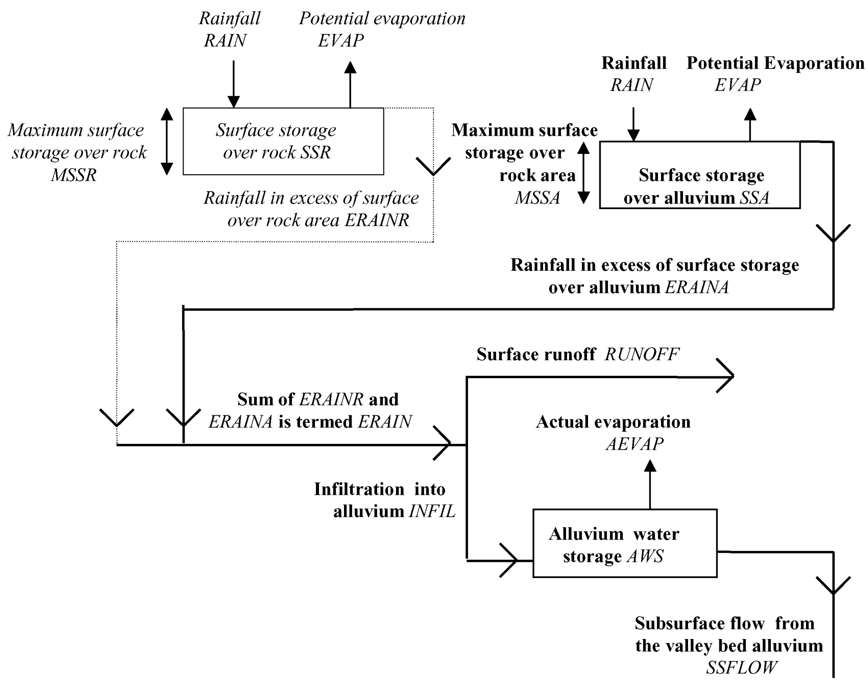
One of the problems with this type of modelling is finding an appropriate mathematical relationship to explain a particular physical phenomenon (Chapman 1990). Furthermore, using a single formula to represent a physical phenomenon, which is heterogeneous even within one subdivision of the catchment, requires a degree of idealisation. The philosophy is to understand the processes involved, and from this understanding, to develop meaningful equations by which an acceptable level of accuracy is achieved. Although the approach has been applied to a specific catchment, it represents the mechanisms of surface and subsurface flow in most catchments with similar hydrological characteristics.

The Principle of the Approach

The approach is based on the concept of routing precipitation within and through the catchment. In this approach, the catchment is divided into three different zones as shown in Fig. 2. In each zone, two materials are recognised: rock and alluvium. The flow is distributed between these zones using expressions that represent the physical processes, but involve only those parameters that are essential. The outflow from each area is inflow to the next area.

The general representation of possible paths of flow, which originate from precipitation and lead to subsurface flow in the valley bed alluvium and surface runoff in the highland area, are shown in Fig. 4. As shown in Fig. 4, in the highland area, the rainfall in excess of the surface storage (SSR) on the bare rock (ERAINR) joins the rainfall in excess of the surface storage (SSA) on the valley bed alluvium (ERAINA). The sum of the rainfall in excess of the surface storage on the bare rocks and alluvium is shown by the symbol ERAIN. Part of the residual rainfall in excess of the surface storage may infiltrate into the valley bed alluvium. The water in the valley bed alluvium denoted by AWS is subject to evaporation and drains into the plain as subsurface flow (SSFLOW), which will reach the aquifer after a delay. The rainfall that is in excess of surface storage and infiltration in the highland area appears as surface runoff (RUNOFF), which either enters the ephemeral rivers or

Fig. 4 Flow diagram showing various routes of rainfall movement in the highland area



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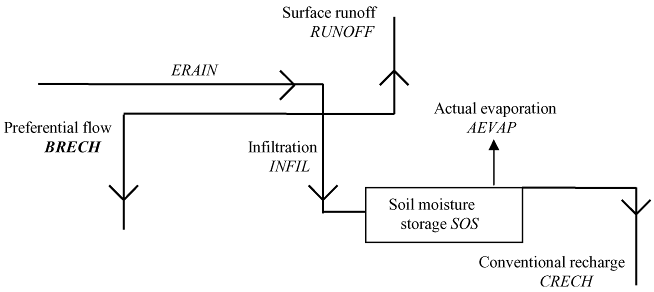

Fig. 5 Flow diagram showing various routes of rainfall in excess of the surface storage in the intermediate and aquifer areas

ponds behind the dams that have been constructed at the outlet of some highland area subcatchments. The ponded water behind the dams is subject to both infiltration and evaporation.

In the intermediate and aquifer areas, the incoming rainfall first satisfies surface storage in much the same way as in the highland area. The residual rainfall in excess of the surface storage, ERAIN, is split into preferential flow (BRECH), infiltration (INFIL) and surface runoff (RUNOFF), as illustrated in Fig. 5. The preferential flow moves through the cracks and macropores of the alluvium avoiding the soil moisture store and may reach the aquifer (Rushton and Ward 1979; Lerner et al. 1990; Rushton 1988). As shown in Fig. 5, the infiltrated water contributes to the soil moisture storage (SOS). The infiltration in excess of the maximum soil moisture storage (MSOS) drains and leaves the soil zone and may reach the aquifer as conventional recharge (Howard and Lloyd 1979; CRECH) or may be evaporated by forming part of the actual evaporation (AEVAP). A delay is applied to represent the time that elapses before the water reaches the aquifer.

The surface runoff that has been created in the catchment joins the ephemeral rivers that are found in the plain areas. Water infiltrating from the bed of an ephemeral river is a good source of groundwater recharge. Surface runoff in ephemeral rivers that does not infiltrate ponds in local depressions, is retained behind the city protection embankments or flows out of the catchment. The ponded water will contribute to evaporation and to infiltration.

Groundwater may be lost from the aquifer by seepage or subsurface flow, a mechanism that is taken into account by the model. Rural and urban development influences the hydrological parameters and allowance has been made in the model for these effects where necessary (Hall 1984; Abu-Rizaiza et al. 1989; Khazaei and Riggi 1999). There are many individual component processes involved in the system. Two are of particular importance and are described in greater detail below.

Infiltration Runoff Process

There is general agreement among investigators that Hortonian overland flow does occur in arid regions (e.g. Freeze 1972; Pilgrim et al. 1979; Yair et al. 1980; Boughton 1988; Ward and Robinson 1990) and this theory is applied here. According to Horton (1933), overland flow occurs when rainfall intensity exceeds the infiltration capacity of the soil. The infiltration capacity of soil varies greatly from point to point within a catchment because the factors controlling it vary. Consequently, considerable idealisation must be accepted in order to formulate the process within a catchment.

For the purpose of the present study, the Porter and McMahon (1971) approach is accepted to estimate the infiltration capacity, INFILC. Their results correspond closely to the observed behaviour of infiltration capacity in well-controlled infiltration experiments. The relationship is:

$$INFILC = CICM \times \exp(-CICN \times \frac{SOS}{MSOS}) \qquad (1)$$

where *CICM* and *CICN* are coefficients, which must be estimated, and the other quantities have been introduced previously. In the highland area, the above formula is used to estimate infiltration capacity, but the values of soil moisture storage (SOS) and maximum soil moisture storage (MSOS) are replaced by alluvium water storage (AWS) and maximum alluvium water storage (MAWS), respectively. The procedure for evaluating the infiltration runoff in the recharge model is first described for the highland area and then for the intermediate and aquifer areas.

Highland Area

As discussed earlier, in most arid regions, highland areas are devoid of soil cover and have steep rocky slopes; depositional soil layers are found only in the valley floors. Hence, infiltration occurs only into the alluvial materials of the valley bed. The rainfall in excess of the bare rock surface storage (SSR), which is denoted by ERAINR, joins the equivalent excess (ERAINA) over surface storage (SSA) on the valley bed alluvium. Both components are available to infiltrate into the valley bed alluvium and their sum is given the symbol ERAIN.

The amount of infiltration from ERAIN into the alluvial material of the valley floors depends on the type of material and on antecedent conditions. To quantify the infiltration into the valley bed alluvium, a value for infiltration capacity is estimated by using Eq. (1). To estimate the amount of infiltration into the alluvial material of the highland area, the following cases may be considered:

1. When ERAIN is less than the infiltration capacity (INFILC), and there is sufficient capacity in the alluvium, the whole of ERAIN infiltrates and contributes to the alluvial water storage. Runoff is zero. When there is insufficient capacity, infiltration occurs until the alluvium water storage (AWS) reaches its maximum. The remaining potential infiltration then appears as surface runoff, denoted by RUNOFF.

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2. When ERAIN exceeds the infiltration capacity, infiltration will take place at a rate equal to infiltration capacity providing the alluvium has storage space available. Runoff is the difference between ERAIN and infiltration capacity. However, should the alluvium water storage impose a limit on inflow, then infiltration occurs until AWS reaches its maximum and excess ERAIN appears as runoff.

Intermediate and Aquifer Areas

The intermediate and the aquifer areas are mainly alluvium with outcrops of solid bedrock in the form of isolated hills. Infiltration occurs over the alluvium and infiltration capacities (INFILC), are estimated for each area from Eq. (1).

The various routes of rainfall movement in the intermediate and aquifer areas, which may lead to preferential flow and conventional recharge, are shown in Fig. 5. In these areas, a fraction of ERAIN enters the alluvium through the cracks and macropores even when there is soil moisture deficit and this is called preferential flow and denoted by BRECH. The remaining ERAIN is denoted by RERAIN. The alluvium in the intermediate and the aquifer areas is permeable and there is enough storage capacity in the alluvium for the infiltration to take place. Therefore, the amount of water that enters the alluvium depends on the infiltration capacity and the amount of RERAIN. All of RERAIN can infiltrate if it does not exceed the infiltration capacity. The response may also be represented as:

– if *RERAIN≥INFILC* then *INFIL=INFILC* and *RUNOFF=RERAIN-INFIL*
– if *RERAIN<INFILC* then *INFIL=RERAIN* and *RUNOFF=0.0*

However, the volume of inflow is proportional to the area exposed to infiltration. The infiltrated water, after bringing the soil moisture to its maximum, may be considered as conventional recharge CRECH. It should be mentioned that there is uncertainty about occurrence of the conventional recharge owing to a lack of understanding of the soil moisture behaviour in arid regions. However, the present study, together with the work of Alderwish and Dottridge (1995), indicates the possibility of conventional recharge in the agricultural part of the catchment. Thus, in order to keep the general applicability of the model, this mechanism is included.

In general it may be said that the method applied in the model for evaluating the infiltration runoff implicitly takes into account the antecedent conditions of the soil moisture and alluvium water storage.

Subsurface Flow from the Highland Area

It can be seen in Figs. 1 and 2 that the alluvial material within the catchment forms a continuous system, although the thickness of the alluvium varies significantly. In the highland area, even when a small amount of rain occurs, some part of it will reach the alluvium because the surrounding rocks are virtually impermeable. Some rain will evaporate at once, some will wet the rock surface and fill surface storage, but the remainder will enter the valley bed alluvium. The water in the alluvium moves along on the sloping impermeable valley bed and enters the plain as a subsurface flow, finally reaching the main aquifer in the plain. The study of Khazaei (1997) indicates that this component contributes more than 50% of natural recharge in the region. The inclusion of this mechanism in a recharge model is considered an important step towards a better representation of catchment behaviour and, consequently, improved estimates of groundwater recharge.

The authors have found no other research, which gives a methodology for evaluating subsurface flow from the valley bed alluvium. The reliability of the method of evaluation depends fundamentally on a clear understanding of the way that water moves through and is stored in the valley deposits.

The physical nature of the alluvium has important consequences for its role in providing flow to the aquifers further downstream. The deposits are thin and they are laid down on impermeable bedrock, which has a significant slope. Difficulties arise in describing the behaviour of such systems because the flow equations are non-linear and because the material can dewater, leading to a moving boundary problem.

In this study, flow through the valley alluvium has been examined using a numerical model developed by the authors. A one-dimensional formulation is adopted that includes a sloping bed and variable saturated thickness. An approximate approach to dewatering and resaturation is employed that gives acceptable results. The non-linear algebraic equations that result from a finite difference formulation are solved by a modified Newton-Raphson method; the over-correction technique, which is an extension of successive over-relaxation.

The model has been validated by comparison with analytical solutions for an idealised sloping bed aquifer under both steady state and time-variant conditions. A typical configuration of the valley alluvium is simulated to illustrate important features of the flow system. Figure 6 shows a typical hydrograph of flow from the alluvium with an impermeable bed slope of 1.6%. The results are for a single recharge impulse of 20 mm applied during the first day. Using the results obtained from the numerical model and certain characteristics of the alluvium, the following formula is introduced to incorporate subsurface flow from the valley bed alluvium in the recharge model.

$$SSFLOW = \gamma Q_o \exp(-\alpha t^{\beta}) \quad (2)$$

where *SSFLOW* is the subsurface flow from the highland area in terms of depth over the alluvium in the highland area (mm/day), $Q_o = \frac{AWS_O \times K \times SL}{S}$, AWS_o is the value of water available in the valley bed alluvium immediately after recharge has occurred in terms of depth over the alluvium area (mm), K is the hydraulic conductivity of the

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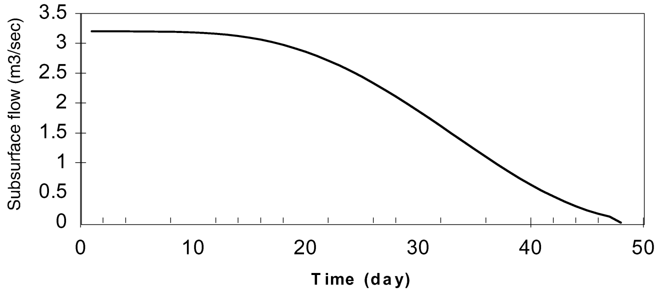

Fig. 6 Subsurface flow hydrograph from the alluvium having hydraulic conductivity of 100 m/day and storage coefficient of 0.01 laying on an impermeable sloping valley bed of 1.6% subject to a single recharge impulse of 20 mm in 1 day

valley bed alluvium (m/d), *S* is storage coefficient of the valley bed alluvium, *SL* is the slope of the impermeable bed, *t* is time (days) and is set to zero at the day when recharge is applied and α, β and γ are constants that must be estimated.

The subsurface flow from the valley bed alluvium joins the preferential flow recharge in the intermediate area, any conventional recharge in the intermediate area and the infiltration from the beds of the ephemeral rivers and forms the main aquifer resource. Infiltration from the beds of ephemeral rivers is estimated by taking into account the lengths and the widths of the ephemeral rivers as well as the type of alluvial material forming their beds.

Model Input and Parameters Estimation

The input data to the model are daily rainfall and daily pan evaporation from the gauges located in the highland, intermediate and aquifer areas. The magnitude of rainfall in the highland area is much higher than the other two parts. For example, in Zahedan catchment, the average annual rainfall in the highland area for the periods 1991-1992 to 1994-1995 is 139 mm (Khazaei 1997), which is almost twice that of the rainfall in the aquifer area (about 70 mm). The parameters of the model are initially estimated within physically meaningful ranges. They may be adjusted further by using sensitivity analyses. Using both an objective function and a visual method can make the comparison between the historical data and the model output.

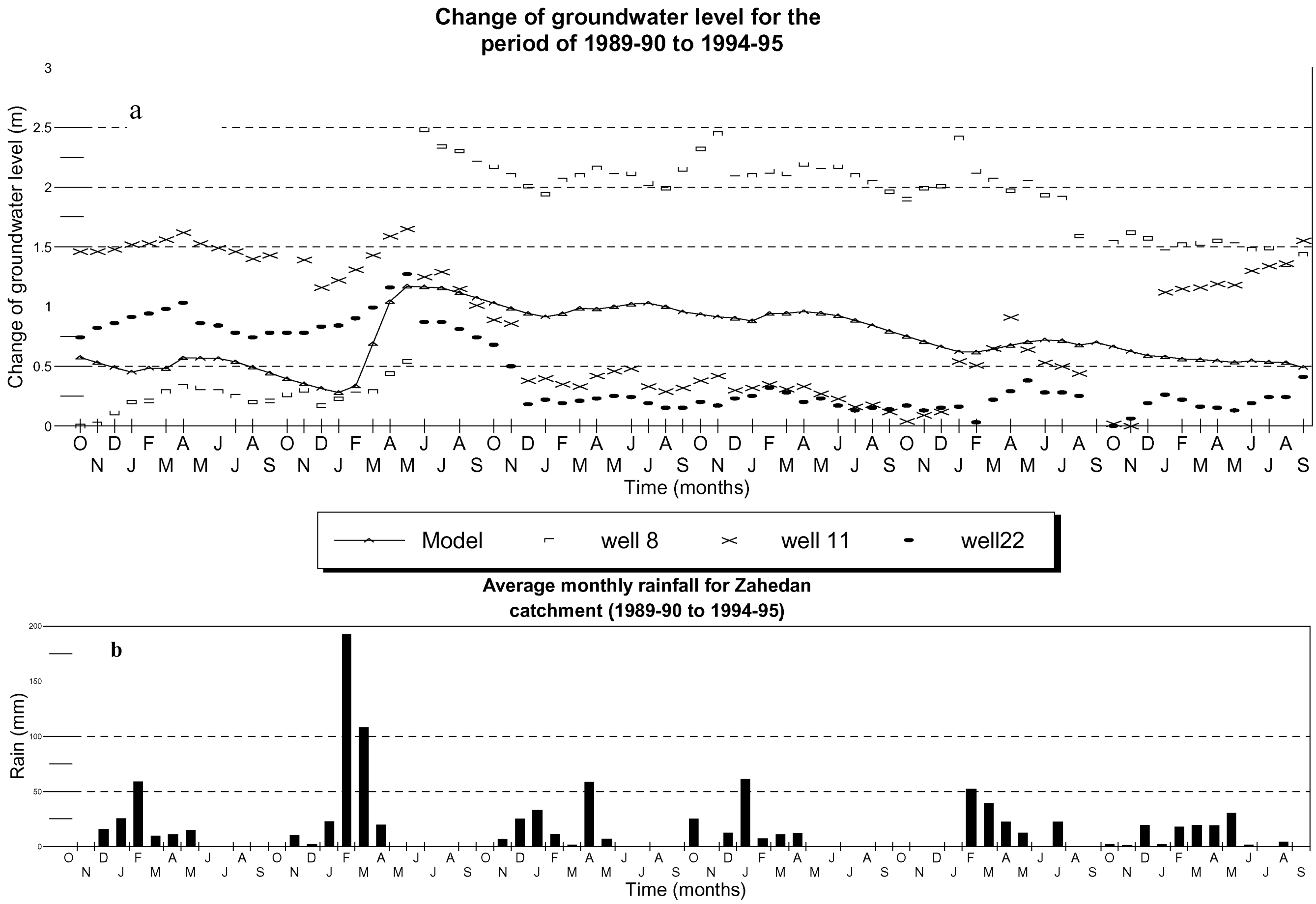

Fig. 7.a Comparison of the changes of groundwater level obtained by the recharge model and groundwater levels in wells 8, 11 and 22 and **b** the weighted average of the rainfall over the Zahedan catchment

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Application to Zahedan Catchment

The recharge model has been applied to the Zahedan catchment in south-east Iran, which has an area of 1,280 km^2. The data from three daily rainfall gauges located in the highland, intermediate and aquifer areas of the Zahedan catchment were used. Daily pan evaporation data was available for one station within the catchment. The parameters of the model were selected within physically meaningful ranges and the model was run for the period October 1989-September 1995.

The daily groundwater recharge generated by the model was used to estimate groundwater-level response. A comparison between groundwater levels obtained from the model and the response in observation wells located in three different parts of the aquifer area is illustrated in Fig. 7. It can be seen that the groundwater level estimated by the recharge model generally has a falling trend, which is in agreement with the general behaviour of the observation wells. The modelled groundwater level generally follows the fluctuations in the observation wells and the magnitudes of these fluctuations are of the same order. Furthermore, the peaks due to rainfall are often matched. The above results are an indication of a reasonably good estimate of groundwater recharge. Some of the discrepancies between the estimated change in groundwater levels and the field observations may be due to uncertainty in the accuracy of the input data. In addition, the results of the recharge model represent overall behaviour of groundwater levels in the aquifer area, whereas the observation wells are often affected by local phenomena such as the extent of urbanisation and the effects of pumping wells.

Sensitivity Analysis

The aim of the sensitivity analysis was to assess the significance of spatial variations in rainfall on the groundwater recharge estimate, which was an output of the recharge model. In this respect, the rainfall data for the highland, intermediate and aquifer areas were applied to the recharge model for the periods of 1989-1990 and 1994-1995 and the recharge obtained was considered as a base for comparison.

To investigate the effect of spatial variations in rainfall, a single test, referred to as test 1, was carried out. In this test, the rainfall from the aquifer area was used to replace the values recorded in the intermediate area and the highland area. The results obtained for groundwater recharge are compared with the base results in Table 1. Table 1 shows that the recharge reduces greatly, by between 42-87%. The above results indicate the magnitude of the error involved in evaluating groundwater recharge if spatial variations in rainfall are not considered.

However, the above results support the approach taken by the authors in which the catchment was divided into different zones of hydrological similarity to account for spatial variability.

Table 1 Sensitivity analysis results

Year	Test number	Recharge	
		Magnitude in Ml/year	Percentage change by comparison with the base
1989–1990	Base	9,988	0.0
	Test 1	2,362	–76.3
1990–1991	Base	33,139	0.0
	Test 1	18,505	–44.2
1991–1992	Base	11,455	0.0
	Test 1	1,383	–87.9
1992–1993	Base	9,873	0.0
	Test 1	5,727	–42.0
1993–1994	Base	12,150	0.0
	Test 1	5,074	–58.2
1994–1995	Base	8,402	0.0
	Test 1	4,010	–52.3

Summary and Conclusions

This paper describes the development of a catchment water balance model for estimating groundwater recharge in the arid region of south-eastern Iran. The specification of the recharge model takes into account the main mechanisms contributing to groundwater recharge in this region and deals with the spatial variation in the mechanisms by dividing the catchment into zones of hydrological similarity. The results obtained from the sensitivity analysis support the division of the catchment into different zones of hydraulic similarity. The development of a methodology for evaluating subsurface flow from the valley bed alluvium, which is the most important component of groundwater recharge in the region, is a substantial improvement in the representation of the catchment behaviour in the region. However, groundwater recharge estimation, particularly in arid regions, is neither easy nor straight forward. Improved results require further research to quantify some of the other mechanisms such as recharge from the beds of ephemeral rivers. There is also a need for a more conscientious effort regarding the collection of the data in the region to provide a basis against which models can be tested more thoroughly.

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