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Modeling the Effects of Rainfall Variability on Groundwater Recharge in Semi-Arid Tanzania

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A conceptual model of the effects of rainfall variability on groundwater recharge was developed and applied to a small forested catchment in semi-arid Tanzania. The model simulated dual-domain recharge through the soil matrix and macropores, and was based on daily values of rainfall and potential evapotranspiration. Three different land-cover conditions (forested-nondegraded, deforested-nondegraded, and deforested-degraded) were included in the study in order to simulate the large-scale deforestation and land degradation process now occurring in Tanzania. In addition, the alternative land covers were also considered in combination with three different rainfall regimes.

The results indicate the importance of macropore flow, particularly during dry years. The lack of macropores under deforested-degraded conditions reduces the simulated groundwater recharge to such an extent that it is less than under forested conditions. Simulating a climate change scenario shows that a small change in rainfall (-15%) can cause a large change in recharge (-45%).

Introduction

The rate of groundwater recharge depends on a complex system of interactions between determinants related to landscape and hydroclimate factors. In contrast to humid, temperate climates, groundwater recharge in the arid and semi-arid tropics is often erratic and may only occur on a few occasions per year. Hence, it is misleading to discuss mean annual recharge rates or to consider recharge as a proportion of mean annual rainfall in such areas, since the recharge rate is determined by the distribution of extreme events in excess of threshold levels (Barnes *et al.* 1994; Lloyd 1986). These conditions indicate that the interface between rainfall characteristics and soil hydraulic properties is central to tropical hillslope hydrology, particularly where land degradation can change the soil properties dramatically (Bonell 1993).

In order to analyze the effects of rainfall characteristics on recharge, it is first necessary to examine the process of groundwater recharge itself. Conventionally, the recharge is attributed to a piston-flow displacement of soil water at field capacity, although many experimental studies have shown that a dual-domain system of recharge operates in most soils (Beven and Germann 1982). In such a system, recharge will occur both through the soil matrix and through macropores. In the former type, the hydraulic conductivity is mainly related to the soil texture and the soil moisture deficit (SMD), whereas in the latter type it also depends on soil structure, which, in turn, is related to land use.

Although macropores may constitute only a small portion of the total soil voids, they can still convey large amounts of infiltrating water deep into the soil profile, under saturated as well as unsaturated conditions (Beven and Germann 1982; Bouma and Dekker 1978). The lateral sorption of macropore flow by the soil matrix can vary in significance; from substantial (Quisenberry and Phillips 1976) to small (Booltink and Bouma 1993). The studies by Germann (1986) and Burt (1989) suggest that macropore flow becomes prevalent under conditions of intensive rainfall and low soil matrix moisture potentials; such investigations are therefore of particular interest to the dry tropics. Summarizing several reports, Beven and Germann (1982) concluded that, depending on antecedent soil moisture conditions, rainfall intensities as low as 1-10 mm h^{-1} may be sufficient to initiate recharge through macropores. Macropores are formed by plant roots, soil fauna, cracks and fissures, and are common in porous and aggregated forest soils but lost after deforestation and soil erosion (Burch *et al.* 1987; Lundgren 1980).

In a previous paper (Sandström, 1995a), the overall interactions between hydroclimate, landscape characteristics, and groundwater recharge in various environments were discussed. In that discussion, the influence of macropores on recharge in dry, tropical environments with fine soils on steep land was emphasized.

Most rural semi-arid and arid tropical societies are highly dependent on groundwater during the dry season. The purpose of this study was to explore the variability in annual groundwater recharge and its relation to rainfall characteristics and land use. In order to do this different rainfall regimes and land-cover conditions were modeled on a small and presently forested watershed in Tanzania in East Africa. It was hypothesized that threshold levels of annual rainfall exist, that these levels determine whether or not groundwater recharge will occur, and that macropore flow is prevalent under low-rainfall conditions.

Method

Study Outline

A simple conceptual model of the implications of rainfall variability on groundwater recharge was developed. Simulations included three alternative land-cover conditions in combination with three different rainfall regimes. The former comprised forested-nondegraded, deforested-nondegraded, and deforested-degraded conditions. Such a series actually forms a sequence of change which is all too common today in Tanzania, *i.e.* a forest is removed, and although favorable soil properties prevail for some time (perhaps a decade or two), certain land management eventually results in land degradation and compacted and structure-poor soils. The three alternative rainfall regimes included in the model were a) the presently prevailing conditions; b) a hypothetical, future climate change scenario, comprising a mean annual rainfall 15% less than today (this was simulated by reducing every event by 15%); c) a future precipitation pattern in which large-scale regional deforestation has led to a change in the distribution of annual rainfall. In Southern India, Meher-Homji (1979) found that the number of rain events declined after deforestation, although the total amount of rainfall was unchanged. In this study the Meher-Homji findings were interpreted as if all rainfall events below 10 mm per day ceased (*i.e.* equal to 18% of the total annual rainfall volume) and that amount were percent-wise equally added to the remaining events (>10 mm). The simulated deforested-nondegraded land-cover conditions were combined only with the current rainfall regime.

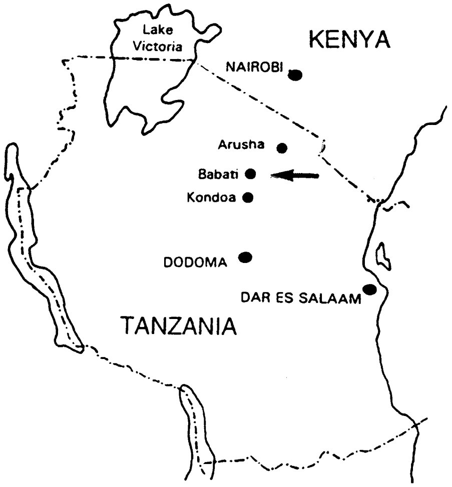

Fig. 1.
The location of Babati town, administrative center of Babati District in north-central Tanzania in East Africa

The Studied Watersheds

The modeled watershed – Harra – is located in the Babati District of north-central Tanzania (Fig. 1). General background information of the area at large has been reported by Strömquist (1992).

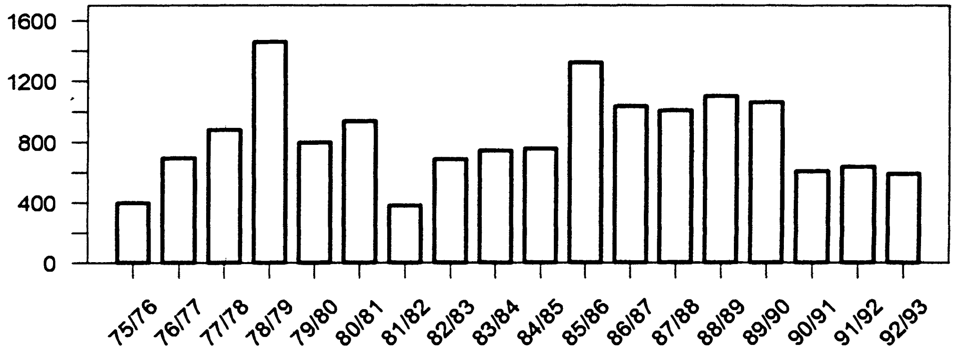

Fig. 2. Annual rainfall (hydrological years) in Babati town, 1975/76 to 1992/93.

Data regarding runoff under deforested and degraded conditions were collected in a nearby watershed (Sigino). The study area has a climate which is typical of the central East African highlands, *i.e.* it is semi-arid (Christiansson *et.al.* 1993) and has a bimodal rain period (November to April) that provides an average (1971-1989) of 807 mm yr^{-1} (Strömquist 1992). A dry season lasts from May to October, and the potential evapotranspiration is approximately 1,660 mm yr^{-1} (Ngana 1992). The daily potential evapotranspiration rate calculated from monthly values was also provided by Ngana (1992). Rainfall data for the hydrological years 1975-1976 to 1992-1993 (1 October to 30 September) is presented in Fig. 2.

Harra is a *Miombo* woodland reserve, a type of dry tropical forest which is common in East and Central Africa. The ground is covered with forest litter, and soil erosion is rare. In Sigino, an argillic B-horizon covers vast areas due to severe soil compaction, surface sealing and sheet erosion. The land is used for farming and grazing. In both watersheds Chromic Luvisols (FAO-UNESCO 1974) cover deep layers of clayloam sapprolite over weathered sedimentary rock, and slopes are moderately steep (20%). Harra is called a »forest« despite being mainly a woodland.

In a previous study (Sandström 1995b) it was found that groundwater recharge via preferential pathways (macropores) was important in forested land (Harra), but appeared to be lost after deforestation and land degradation (Sigino). The annual recharge rate in Harra was estimated by using the chloride method in baseflow discharge and by standard runoff gauging. Excluding large evapotranspiration losses from a perennial discharge area, recharge amounted to 100 mm yr^{-1}; approximately 70% of that amount percolated through macropores and 30% through the soil matrix. The recharge rate was regarded as representing an average of a fairly long period of time, maybe a decade, since a groundwater aquifer has a levelling effect on the discharge rate and concentration of chloride. In the cited study, soil moisture measurements were made in deep profiles (5-10 m) at numerous locations in Harra and Sigino on three occasions; in April 1992, in December 1992, and in April 1993. The field capacity was calculated from the soil texture and from the data on water properties of Tanzanian soils provided by McKeague *et al.* (1991). Data on rainfall and corresponding overland flow in Harra and Sigino were reported by Sandström (1995b). Daily rainfall data were collected from the meteorological station at nearby Babati Agricultural Station. Maximum interception (derived from the throughfall of approximately 105 rainfall events into 5 large (each 0.49 m^2) collectors was found to be 2.1 mm per rainfall event in Harra (unpublished data) and was arbitrarily set to 0.5 mm in an open, Sigino-resembling environment.

In a study on groundwater recharge in relatively nearby and also semi-arid Zambia, Houston (1982), provided conversion factors for pan evaporation to evapotranspiration for different types of vegetation (open forests: 0.84, short vegetation: 0.68). The »open forest« vegetation consisted of the same *Miombo* type of trees as found in Harra. However, a slightly lower value, 0.8, was used in Harra, since the area is a woodland, not a forest, and partly covered by a mixture of small trees, large bushes and tall grasses. In Sigino the short vegetation value of 0.68 is appropriate of a combination of grass and food crops. In addition, in the present study the potential evapotranspiration rates provided by Ngana (1992) were used instead of the pan evaporation rate.

The Rainfall Variability Model

The basic structure of the model is shown in Fig. 3. The design is typical of conceptual hydrological models, for example the HBV-model (Bergström *et al.* 1985). The model takes into account daily rainfall, P_d, and potential evapotranspiration, Ep_d,

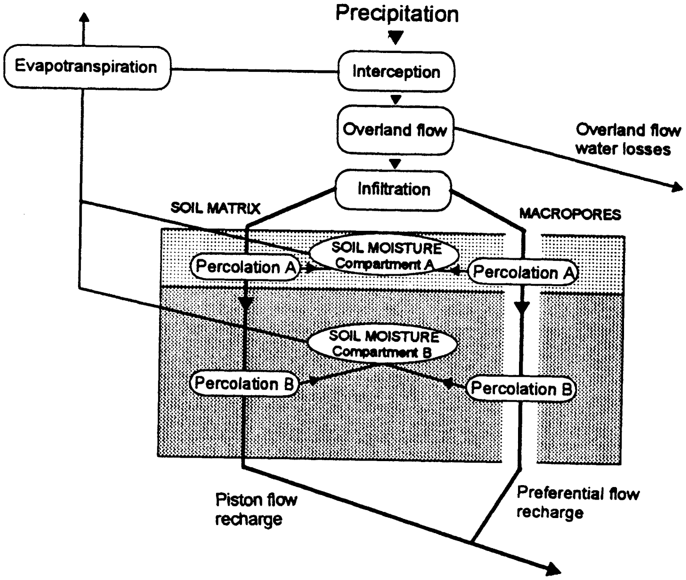

Fig. 3. Schematic structure of the applied model.

values (the latter calculated from monthly values), a loss of surface water by overland flow, and the division of infiltrating water into a dual-domain recharge system. The actual evapotranspiration, Ea_d, for the two soil compartments was calculated daily. A two layered compartment approach was chosen to allow large *SMD* (soil moisture deficit) fluctuations in the upper compartment between and during different seasons, since the *SMD*s in that layer control subsequent macropore flow into the soil profile (Germann 1986).

The Ea_d was determined by employing the interception, *IC*, and the evapotranspiration rates for the two soil compartments. The *IC* was given by a parameter, whereas the indicated rates were calculated separately for soil compartments A (0-1 m) and B (1-4 m) by using the equation

$$\frac{Ea_{dA,B}}{Ep_d} \equiv \left(\frac{FC-SMD}{FC}\right)^{\text{constant}} \tag{1}$$

where *FC* is the soil field capacity, and the constant represents α and β, parameters used for soil compartments A and B, respectively. This type of routine was selected since it provides a function which continuously adjusts the Ea_d/Ep_d ratio to the SMD (which is unlike *e.g.* the Penman root constant model) and also received very good ratings in an assessment by Calder *et al.* (1983). The function is plotted in Fig. 4.

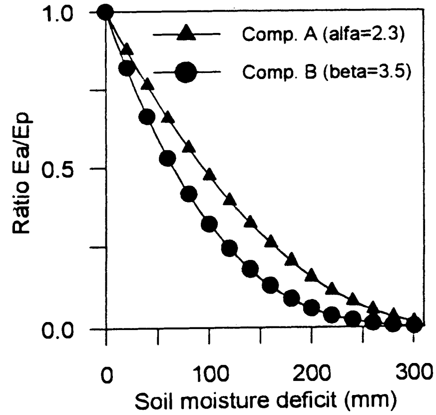

Fig. 4. The form of the functions used to determine the actual soil evaporation Ea_{dA} and Ea_{dB} for two soil compartments, A and B, from the potential evapotranspiration E_{pd}.

The *FC* was a preset constant (0.36 (vol), equal for both compartments), whereas a new *SMD* value was calculated daily from the *SMD* of the previous day, deducting for both infiltration via the soil matrix surface and adsorption through macropore walls, and adding for evapotranspiration losses and downward percolation.

Total Ea_d was determined from the following conditions:

IC = P if $P < IC$; else 2.1 mm (forest) and 0.5 mm (grassland)
Ea_d = $IC + Ea_{d,A+B}$ if $IC + Ea_{d,A+B} < Ep_d$, or
Ea_d = Ep_d if $IC + Ea_{d,A+B} > Ep_d$ which implies that the actual rate is
$Ea_{dA+B} \equiv Ep_d - IC$. This value is divided between $Ea_{d,A}$ and $Ea_{d,B}$ in such way that the ratio $Ea_{d,A}$ to $Ea_{d,B}$ calculated in Eq. (1) is maintained.

The overland flow, Q_o, was calculated from data on rainfall and runoff in Sandström (1994b). On average, the total overland flow in Harra and Sigino was found to be 0.7 and 5% of annual rainfall, respectively.

At the soil surface, the remaining net rainfall ($P_n = P - IC - Q_o$) was divided by a parameter (Infil) which determines if water will infiltrate into the soil matrix or into macropores. It is a parameter which is related to the distribution and »number« of macropores and to the rate of infiltration into the different soil domains. The division of infiltrating water will be further discussed in subsequent sections.

The subsequent percolation through the two recharge domains (Fig. 3) will proceed at rates calculated by the equations

$$Rm \equiv \left(\frac{FC - SMD}{FC}\right)^m P_n \, \mathrm{Infil} \tag{2}$$

$$Rp \equiv \left(\frac{FC - SMD}{FC}\right)^p P_n \, (1 - \mathrm{Infil}) \tag{3}$$

where m and p relate to soil matrix and macropore percolation and the respective percolation constants. Since a proportionality between infiltration into the macropore domain and the subsequent macropore percolation exists in the model, a low macropore flow reduction should be included. The limit was set at 3 mm of water infiltrating the macropore domain, and whenever there was this amount of infiltrating water, or less, the calculated percolation flow (Eq. (3)) was multiplied by the infiltrating amount divided by 3.

The model calculates percolation through soil compartment A, and the accompanying changes in SMD and Ea_{dA}, and then the passage through compartment B, also with the accompanying changes in SMD and Ea_{dB}. Velocities of flow in macropores were assumed to be non-limiting. The final drainage below 4 m of depth forms the daily total groundwater recharge, as the root zone is mainly found above that level (Jeffers and Boaler 1966).

The parameters which were given different values depending on land-cover conditions were the IC (interception), the overland flow (resembling either Sigino or Harra conditions), the infiltration parameter (related to the macroporosity of the soil), and the potential evapotranspiration conversion factor (forest or grassland).

Model Calibration

Since data on annual recharge were not available, it was concluded that it would only be possible to model the relative changes of recharge from year to year as a function of rainfall variability. Hence, following calibration, the mean modeled recharge rate for the entire 18-year period (1975/76-1992/93) of forest conditions equals the measured mean recharge rate and the relative amounts of matrix and macropore flow (*i.e.* 30:70, per cent of total recharge) (Sandström 1995b). Several other studies have also indicated that macropore flow makes large contributions to the total recharge (Sharma and Hughes 1985; Booltink and Bouma 1993; Germann 1986). In addition, *SMD* values for three separate occasions were also used in the calibration of α, β, m, and p (3.8, 1.1, 2.3, and 3.5, respectively). The subdivision of infiltration into the soil matrix and the macropores was assigned to be 95:5 on degraded land (per cent of infiltrating water). This ratio was hypothesized, but chosen in order to represent degraded and compacted Sigino soil conditions, where the vegetation is poor and a clay surface layer exists. Thereby it also clearly differs from the nondegraded Harra ratio of 70:30. To supply enough water to simulate 70% of the total recharge by macropores on nondegraded Harra conditions, it was necessary to allow 30% of the remaining net rainfall, P_n, to infiltrate the macropores. Please note that there are two different »70%« values: total recharge by macropore flow, and infiltration into the soil matrix. If there had been a smaller amount of macropore infiltration, the calibrated percolation parameter values would have indicated an almost direct and adsorption-free recharge; a kind of percolation which is very unlikely to occur. Starting SMD_A and SMD_B values were derived from soil samples collected at appropriate depths during the dry season of 1992.

Results

Modeled Results

Results are presented for two intervals: a short, initial 5-year period (1975/76 to 1979/80) and the entire 18-year period (1975/76 to 1992/93). Since the model was not expected to generate reliable data on *absolute* recharge rates, the findings given in the figures and tables should be regarded as relative, not absolute.

Data on daily rainfall and modeled matrix and macropore recharge (under forested conditions) for the 5-year period are presented in Fig. 5. During this period, the amount of rainfall rose from an initially low 397 mm yr^{-1} to a very high 1,457 mm yr^{-1}, and thereafter declined again (Fig. 2). It is apparent from Fig. 5 that varying amounts of rainfall have a direct effect on recharge. During the first two years, recharge was small and was dominated by macropore flow. On the other hand, in the wettest year (1978/79), recharge was both large and relatively evenly divided between the two flow domains.

Recharge as related to the distribution of rainfall is illustrated in Fig. 6 for forested-nondegraded conditions. When the cumulative amount of recharge (both types, as percent of annual totals) is plotted against a cumulative series of ascending rainfall events (also as per cent of annual totals), a difference develops between the dry

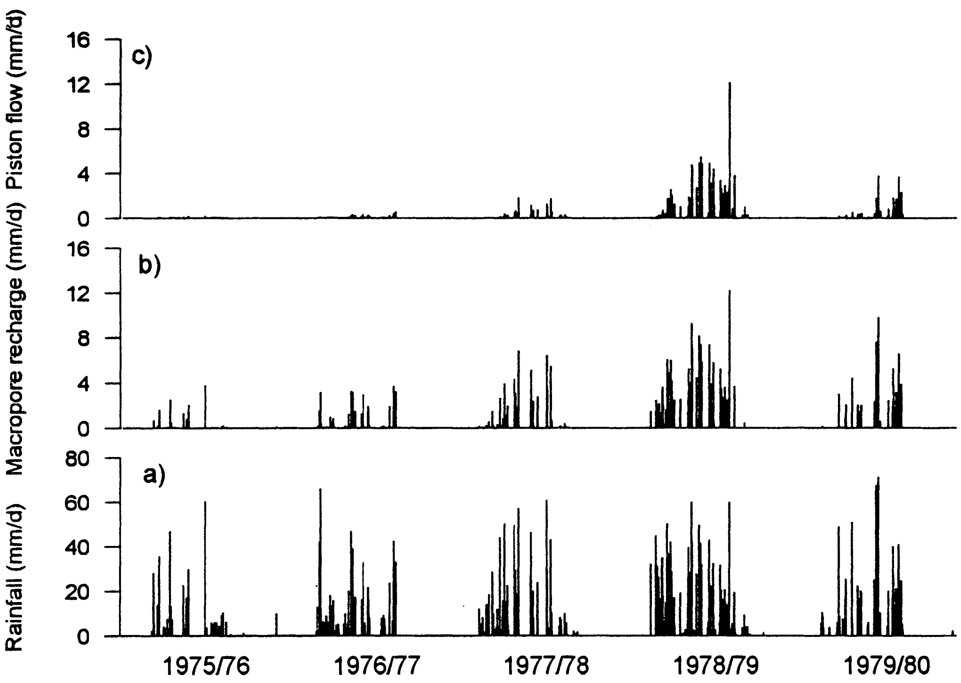

Fig. 5. Daily rainfall amounts a) and modeled macropore b) and soil matrix recharge c) during the five-year period 1975/76 to 1979/80 (hydrological years). Since the modeled results are relative, the abscissa scale in the diagrams should be regarded as relative (see text for further information).

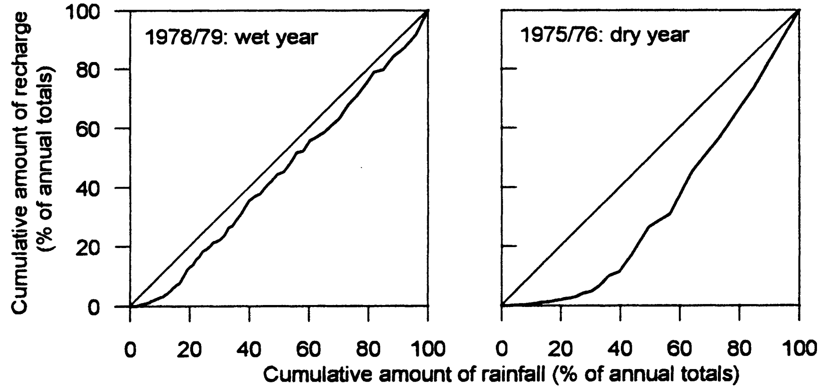

Fig. 6. The cumulative amount of recharge (both types, as percent of annual recharge) plotted against a cumulative series of ascending precipitation events (also given as per cent of annual totals) during a wet year (1978/79) and during a dry year (1975/76).

Table 1 - Mean modeled results (for the 18-year period) of recharge under 3 alternative types of land cover conditions and 3 different rainfall regimes. The data on per cent recharge is compared to the prevailing rainfall regime and forested, non-degraded conditions. All recharge values are given in mm and are relative (see text for further information)

Rainfall regime & recharge type (mm yr^{-1} & %)	Land cover condition Forested-nondegraded	Deforested-nondegraded	Deforested-degraded
P (normal)			
R_p	71	87	4
R_m	30	46	80
R-total	101	133	84
%	100	131	83
P (-15%)			
R_p	47		2
R_m	13		41
R-total	60		43
%	59		42
P (M-H rainfall)			
R_p	89		6
R_m	36		91
R-total	125		97
%	124		96

line. The results are presented in Table 1. An important finding is the dramatic loss of recharge when total rainfall was reduced. Annual recharge was decreased by about 50% (particularly under deforested and degraded conditions) when the total rainfall was lessened by only 15%. In contrast to this, the Meher-Homji (1979) type of rainfall, stressing large rainfall events, increased recharge under both nondegraded and degraded conditions, and primarily through macropores.

Sensitivity Analysis

The analysis was performed on the six parameters used in the model, *i.e.* α and β, m and p, the division of the infiltrating water, and the low macropore flow reduction. The analysis was undertaken on forested-nondegraded conditions for the initial 5-year period, and the results are presented in Fig. 9. The ordinate represents positive and negative changes of each parameter (in per cent), and the abscissa the corresponding effects of the change on the total recharge rate (as per cent of change).

The sensitivity analysis showed, for example, that increasing the values of α and β reduced evapotranspiration and therefore increased recharge, and that a decrease in the loss of water from low macropore flows gave the same result. Similarly, the

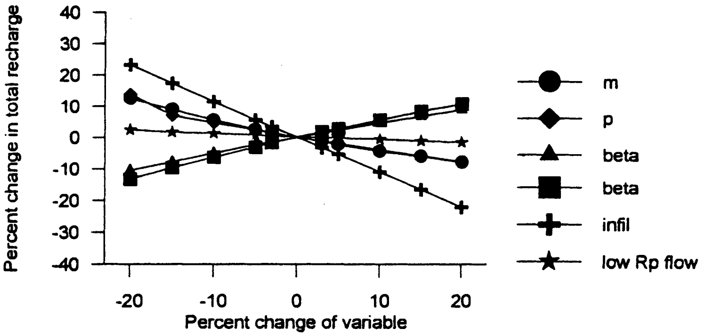

Fig. 9. The results of the sensitivity analysis. The ordinate represents positive or negative changes of each variable (in per cent), and the abscissa the corresponding effect on the total recharge rate (as per cent of change).

percolation rate was reduced by increasing the values of *m* and *p*. These changes had a relatively small effect on the recharge rate, *i.e.* the rate only changed about half as much as the parameter. In contrast to this, the model was sensitive to the division of water into matrix or macropore infiltration. When the ratio of soil matrix infiltration was raised by 20%, the recharge was reduced by 20%, as less water was directed into the macropores, through which recharge is rapid and efficient.

Discussion

It is essential that a model used in the dry tropics incorporates daily values of rainfall if the heavy and erratic rainfall events typical of such areas are to be satisfactorily simulated. Unless recharge calculations are based on short data periods, the recharge may be significantly underestimated (Rushton and Ward 1979). In addition, the soils in these regions are often very dry (well below field capacity), which requires a model with a dual-domain recharge function to adequately simulate the recharge process. Although some attempts (*e.g.* Houston 1982) have been made to use the Penman-Grindley type of model (Grindley 1967) in the dry tropics, it seems unlikely that that type of model can provide accurate results. In Penman-Grindley type models, actual evapotranspiration is calculated by the use of root constants, and recharge is assumed to occur after the field capacity is reached; both of these principles are probably better suited for use in humid, temperate regions.

In absolute terms the presented result has low accuracy, although in relative terms, the inter-annual variability and the ratios between different recharge modes are regarded to be more reliable. It should be noted that the very large recharge variability between wet and dry years, together with the subsequent different ratios between soil matrix and macropore flows were unexpected results. In the sensitivity analysis, the recharge rate was not unusually affected by the parameter values. The only exception to this was the division of water into soil matrix and macropores. Varying this division gave large changes in total recharge, although that was expected. The model was calibrated to supply 70% of total recharge via macropore flow, so a change in soil macroporosity, *i.e.* a function of the amount of water entering the macropore domain, naturally gave a large change in recharge.

Results obtained with the modeled watershed showed that every year during the dry season, large soil moisture deficits developed that lasted well into the wet season. But of particular importance was the ability of the macropores to generate recharge also under dry years. In a dry soil with a large *SMD*, like that in 1975/76 (Fig. 7), very little water percolated through the soil matrix, and recharge depended mainly on macropore flow. Under forested-nondegraded conditions (as in Harra today), approximately 90% of all recharge was conveyed through macropores during the dry years, whereas during the wet years, both types of recharge were of the same magnitude. Related to this pattern is the distribution of modeled rainfall events and their corresponding recharge distribution: during wet years, most rainfall events were able to generate recharge, whereas under dry conditions (when the *SMD* was high), it was mainly the large events that were able to generate recharge.

The deforested-nondegraded land showed by far the largest recharge rate, which is not surprising. The recharge increased by roughly 30% as compared to recharge under forested conditions. With the evapotranspiration rate minimized, the *SMD* was reduced and percolation was favored through both of the two recharge domains. It is interesting to note that the 30% difference in recharge between forested and deforested land corresponds to a rough average of the values reported by most worldwide paired catchment studies on runoff from forested and deforested land (see review by Bosch and Hewlett 1982).

However, when the modeled land was converted to deforested-degraded conditions, the transpiration rate was reduced and the soil lost its, to percolation, favorable structure. The latter, in combination with lost infiltration opportunities and larger losses of water through overland flow (Sandström 1995b), reduced the simulated macropore percolation to only a trickle, regardless of whether it was a dry or a wet year. During wet years, a reduced transpiration rate had a beneficial effect on total recharge (Fig. 8), whereas during dry years the total recharge was reduced to only about a third compared with forested-nondegraded conditions (Fig. 8). On average, annual recharge under deforested-degraded conditions was 83% of the recharge under forested-nondegraded conditions. This result can be compared with the actual Sigino baseflow rate, being 56% of the baseflow in Harra (Sandström 1995b). The simulated result may seem controversial to most catchment studies (*e.g.* Bosch and Hewlett 1982). However, when deforestation in the dry tropics is followed by land degradation, baseflow can decrease (Pereira 1991; Christiansson *et al.* 1993).

Some reports of global-scale simulations of future terrestrial hydroclimates by general circulation models, *GCM*'s, have presented derived results with direct implications on human welfare, *e.g.* soil moisture predictions (Gleick 1986; Manabe and Wetherland 1986) and the CO^2 response of plants (Mooney and Koch 1994). Charney (1975) modeled a reduction of vegetation in the Sahel region south of the Sahara and found that rainfall decreased by about 40%. In the present study, a simulated 15% reduction in annual, long-term rainfall revealed an immense effect on recharge, *i.e.* it was reduced by between 40 to 50%, particularly on deforested and degraded land. The alternative rainfall distribution, in the present study referred to as the Meher-Homji (1979) type of rainfall, which stresses large but few events, had a small but positive effect on total recharge, but, again, primarily in land with an abundance of macropores. Altogether, since rural life in East Africa depends on groundwater for at least 6 months out of each year, these result are appalling if future climate-change implications would imply a loss of rainfall. The present study results agree well with the conclusion Gleick (1986) arrived at by summarizing several reports, *i.e.* a small change in rainfall or evapotranspiration might cause a large change in water availability.

Conclusions

The present model was calibrated against the mean recharge rate value and the division of that value into soil matrix and macropore flow. It was therefore unlikely that reliable *absolute* data on annual recharge rates would be obtained. However, in relative terms, the variability and ratios between soil matrix and macropore flow are regarded to reflect the fluctuations in rainfall over an 18-year period of alternating wet and dry years. The foremost result of this study is the large amplitude of variability the recharge display as compared to the fluctuations in rainfall, and the importance of macropores for total recharge. According to the model, groundwater recharge was fairly equally subdivided between the soil matrix and the macropores during wet years, whereas during dry years macropores conveyed almost all of the recharge. This effect was amplified under simulated deforested-degraded conditions: macropore recharge was marginal, and during dry years the total recharge was reduced to only a third of that seen under forested-nondegraded conditions.

A simulated 15% reduction in annual rainfall implied a reduction of 40 to 50% in annual groundwater recharge. This is an alarming result, since some *GCM* simulations of future climate change indicate a reduction in long-term rainfall amounts, and rural life in the semi-arid tropics depends on groundwater resources for many months each year.

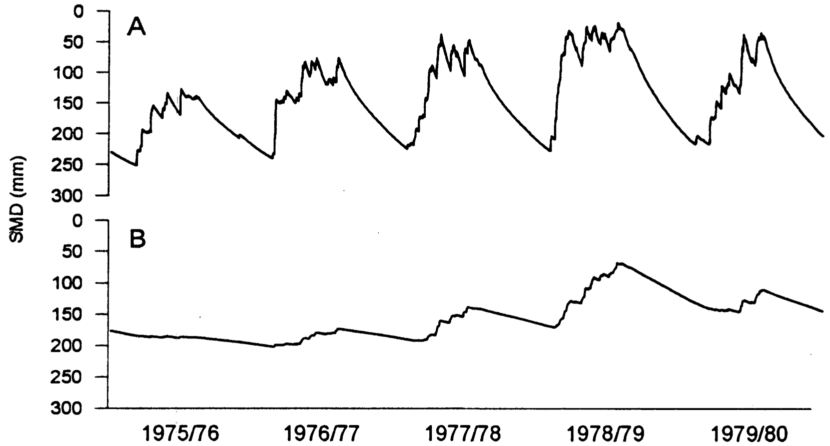

Fig. 7. The soil moisture deficit in compartments A (a) and B (b) during the five-year period 1975/76 to 1979/80 (hydrological years).

year of 1975/76 and the wet year of 1978/79. In the wet year, almost all rainfall events generated recharge, *i.e.* the lightest rainfall events, representing 50% of annual total, also provided about 50% of all recharge. In the dry year, however, an imbalance developed, *i.e.* the same portion of the rainfall events provided only about 25% of the recharge.

The *SMD* of the two compartments designated A and B are presented in Fig. 7. In compartment A (upper curve), the soil was drier and the *SMD* fluctuated more each year than in compartment B (lower curve). The increasing amounts of rainfall over the first four years are evident: during the rainy seasons the soil became increasingly wet, although during the dry seasons it dried out and returned to a fairly constant moisture level. This was true in particular for compartment A; changes in compartment B were slower and more stable. Directly observed upper and lower compartment *SMD*s in Harra in April-92, Dec-92 and April-93 (wet-dry-wet seasons) were 195:310:170, and 210:247:172, respectively. The simulated values all indicated wetter conditions, between 5 and 22% lower *SMD*. The observed values can be compared with the period 1975 to 1977 in Fig. 7, two years with about the same total annual rainfall.

Data on recharge for the entire 18-year period are presented as relative annual totals. In Fig. 8a recharge under the three alternative land-cover conditions is plotted against annual rainfall. Exponential curves of best fit gave r^2 values between 0.80 and 0.85. The division between matrix and macropore recharge is presented for each of the three alternatives, as the ratio between macropore and matrix recharge (Figs. 8b, c and d). Table 1 shows the means of the three alternatives for the 18-year period. The simulated recharge rate under deforested-degraded conditions is compared with actual recharge values under similar conditions (Sigino) in the discussion.

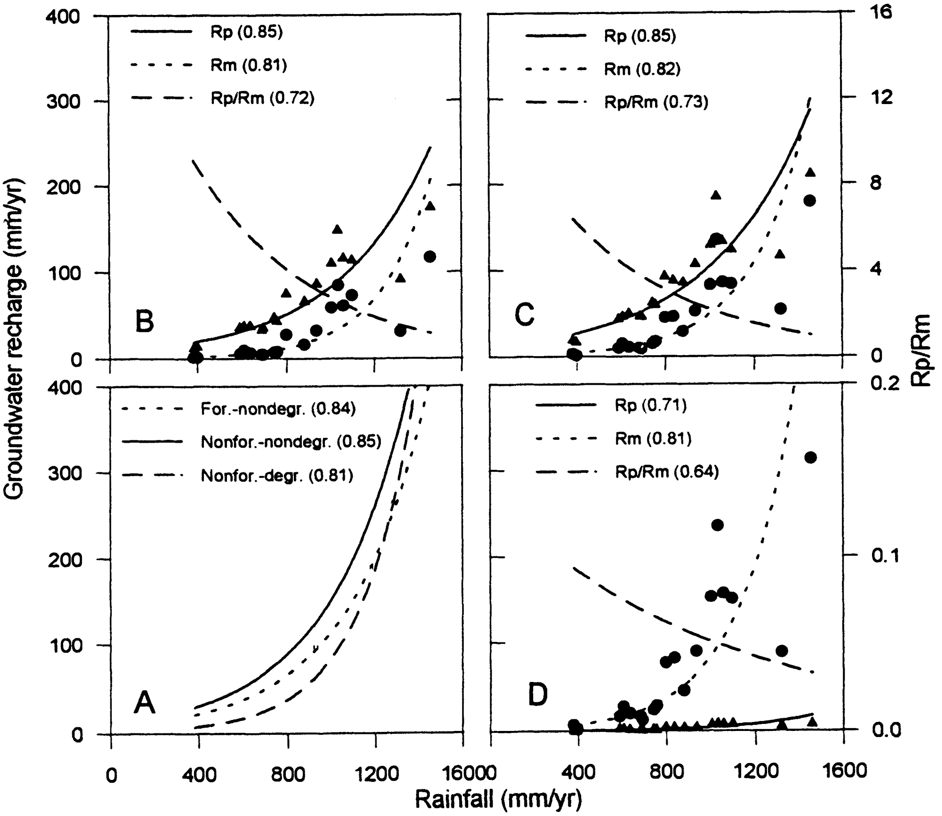

Fig. 8. The total annual modeled groundwater recharge rate plotted against annual rainfall amounts under three alternative types of land-cover conditions, *i.e.* forested-nondegraded, deforested-nondegraded, and deforested-degraded land (Fig. a). The division of total recharge into macropore and soil matrix recharge, and the ratios between macropore and soil matrix recharge, are displayed under the same conditions in Figs. b, c and d, respectively. The r^2 of each curve is indicated. The values representing recharge rates should be regarded as relative (see text for further comments).

Apparently, recharge through macropores was important under non-degraded conditions, particularly during years with little rainfall. During such years, approximately 90% (or more) of the total recharge was conveyed through macropores, while the matrix flow contribution was marginal. However, it was evident that during dry years (<500 mm), very little recharge occurred under deforested-degraded conditions, although some recharge still occurred under both forested and deforested-nondegraded conditions. Under degraded conditions, it appears as if 400 mm of annual rainfall has to be exceeded before any recharge will occur.

Recharge under forested-nondegraded, and deforested-degraded conditions were also simulated with two alternative rainfall regimes, as described in the study out-

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