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Abstract: The understanding and quantification of groundwater recharge in semi-arid areas is fundamental to sound management of water resources in such areas. A soil water balance model, if designed to adequately represent the physical processes involved, and if carried out with a short enough (daily) time step, can provide realistic estimates of deep drainage (potential recharge) over long periods.
We describe a single store (single layer) mass water balance model applicable to semi-arid areas, which recognises the wetting of the near-surface during rainfall, with subsequent availability of water for evaporation and transpiration in the days following rainfall. The model allows for the major hydrological processes taking place at or near the soil-vegetation surface including runoff.
Model results are presented for north-east Nigeria, for a continuous period of 36 years during which mean annual rainfall was 431mm (range 321-650mm) and mean annual modelled deep drainage was 14mm (range 0-95mm, with 23 years having zero potential recharge). The results show clearly that annual recharge bears little relation to annual rainfall. The temporal distribution of daily rainfall and the magnitude of the antecedent (pre-season) soil moisture deficit are the strongest determinants of deep drainage at a particular location, in a particular year. Sensitivity analysis of soil and vegetation parameters suggests that deep drainage is most sensitive to water holding capacity and rooting depth. These are key parameters which determine spatial variability of potential recharge.
The model is shown to be plausible by examination of the concepts which underlie it, by comparison with field soil-moisture measurements, and by the model's ability to represent qualitative observations of crop yield variations from year to year.
Future development of the model could include applications to other climatic conditions and the inclusion of other hydrologic processes.

*** Revision Notes**
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GEODER3066R1

Revision Notes

Reviewer #1: The paper is now much clearer and will make an excellent publication. Many of the comments have been satisfactorily addressed.

There are three very minor issues that should be addressed:

Abstract:

1. line 20 - 21. This comment is still too bold within the abstract: First it is the modelling that indicates that the annual rainfall is not a good predictor, not the data. Secondly, and more importantly, Figure 8 clearly shows a statistical relationship between annual rainfall and modelled potential recharge. Please change to something like "The modelling results indicate that annual rainfall totals are not the main predictor of annual recharge." Linked to above in the body of the paper at lines 429 - 431 - remove convincing. Change to something along the lines of "Figure 8 demonstrates that in semi arid areas annual rainfall totals are not a good predictor of annual potential recharge".

THIS ADVICE HAS BEEN INCORPORATED IN FULL.

2. Lines 30 - 31 are not suitable for the abstract, since do not reflect whats in the paper. Change to something like "Future development of the model could include applications to other climactic conditions and the inclusion of other hydraulic processes."

THIS ADVICE HAS BEEN INCORPORATED IN FULL.

3. 624 - 626. Here the output is compared to edmunds's work in Northern Nigeria. However mot enough information is included for the reader. It needs to be clarified that the model is being compared to data that was collected using the chloride profiling technique and that these results showed an average annual reharge of XXX - consistent with the modelled results.

LINES 624-626 HAVE BEEN EXPANDED ALONG THE LINES ADVISED.

* Marked Manuscript

A Single Layer Soil Water Balance Model for Estimating Deep Drainage (Potential Recharge): an Application to Cropped Land in Semi-Arid North-East Nigeria

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Abstract

The understanding and quantification of groundwater recharge in semi-arid areas is fundamental to sound management of water resources in such areas. A soil water balance model, if designed to adequately represent the physical processes involved, and if carried out with a short enough (daily) time step, can provide realistic estimates of deep drainage (potential recharge) over long periods.

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Model results are presented for north-east Nigeria, for a continuous period of 36 years during which mean annual rainfall was 431mm (range 321-650mm) and mean annual modelled deep drainage was 14mm (range 0-95mm, with 23 years having zero potential recharge). The modelling results indicate that annual rainfall totals are not the main predictor of annual recharge. The temporal distribution of daily rainfall and the magnitude of the antecedent (pre-season) soil moisture deficit are the strongest determinants of deep drainage at a particular location, in a particular year. Sensitivity analysis of soil and vegetation parameters

suggests that deep drainage is most sensitive to water holding capacity and rooting depth. These are key parameters which determine spatial variability of potential recharge.

The model is shown to be plausible by examination of the concepts which underlie it, by comparison with field soil-moisture measurements, and by the model's ability to represent qualitative observations of crop yield variations from year to year.

Future development of the model could include applications to other climatic conditions and the inclusion of other hydrologic processes.

Keywords: Deep drainage, Potential recharge; Evapotranspiration; Nigeria; Semi-arid; Soil water balance.

1. Introduction

In semi-arid areas, the question of whether and under what conditions groundwater recharge occurs, and its magnitude, are fundamental to the management of water resources. Questions of spatial and temporal variability, as a function of soil, vegetation, and weather properties, are also basic to the understanding of the hydrology of such regions.

Estimating deep drainage (also referred to in this paper as potential recharge) in semi-arid environments is difficult for several reasons. First, the re-distribution of rainfall by the runoff process, and consequent localisation of infiltration and deep drainage would lead to a high degree of spatial variability of deep drainage, even were there no spatial variations in soil and vegetation properties. When soil and vegetation variations are considered too, the problem of spatial variability is compounded.

Second, the re-distribution of infiltrated rainfall in the soil profile, and its uptake by roots of crops and natural vegetation are complex processes. Our ability to adequately represent these subtle processes in multi-layered soil models incorporating assumptions about root-water uptake is so far rather limited. We suggest here that a modified single store (single layer) soil water balance model which makes few assumptions about the depth from which roots prefer to extract water, can adequately represent the processes involved, and provide reliable estimates of groundwater recharge under cropped land in semi-arid areas.

Third, in semi-arid environments the estimation of deep drainage is challenging because the potential evapotranspiration is invariably much larger than the rainfall. Consequently doubts have been expressed about the suitability of the soil water balance technique. Hendrickx and Walker (1997) consider that soil moisture budgeting models are of limited use since they are prone to large errors in recharge rates. This is a valid criticism when the model fails to represent soil and crop conditions, or uses too long a time step. The longer the time step, the greater the numerical similarity between infiltration and actual evapotranspiration, and hence the smaller the difference (deep drainage) between the two, and consequently the greater the possible error.

Field experiments for quantifying deep drainage, such as the use of natural or artificial tracers (eg chloride) or consideration of the movement of water in the unsaturated soil zone (Hendrickx and Walker 1997; Edmunds et al, 2002), provide valuable insights into the recharge processes but they are not suitable for routine estimation of potential recharge over large areas, or over long time periods. The soil water balance method is an alternative approach. If it provides a reliable representation of conditions for the crop and the soil, acceptable potential recharge estimates can be obtained.

A detailed review of alternative methods of estimating recharge, including soil water balance models, is provided by Kendy et al. (2003). An early example of potential recharge estimation in North-eastern Jordan using a soil water balance (Lloyd et al. 1967) demonstrates the viability of this approach.

Soil water balances are used widely in hydrological studies, but they vary in their features because the components included in the balance depend on the objectives of the study. Water balance methods are widely used for estimating crop water requirements in semi-arid areas as described in the FAO Irrigation and Drainage Paper 56, Crop Evapotranspiration (Allen et al. 1998). The methods described in that report are based on extensive field experience.

In order for the methods described by Allen et al (1998), and by us, to be used for regional potential recharge estimates, further work is needed on the appropriate lumping or discretisation of soil and vegetation properties over large areas with mixed bare soil, crop cover, and sparse shallow- and deep-rooting natural vegetation.

The conceptual and computational models described in this paper are intended for point estimates of deep drainage where daily rainfall records are available together with information about the reference crop potential evapotranspiration. From information about the soil, the crop and bare soil evaporation, estimates are made of the actual evapotranspiration throughout the year. No unnecessary complexities are included in the methodology.

The paper first presents (in section 2) the individual physical processes which together contribute to the conceptual model of the changing conditions in the soil and crop. These form the basis for the soil water balance calculations (presented in section 3, and applied there to Nguru, one of two sites in North-East Nigeria – see below). The conceptual and computational models must reflect the relevant properties of the soil, the nature of the crop, the growth of roots, the potential evapotranspiration from both the crop and from bare soil, the reduced evapotranspiration due to limited moisture availability and the conditions under which recharge can occur.

Section 4 of the paper further discusses the application of the model to Nguru and Maiduguri, two sites approximately 300km apart in semi-arid North-East Nigeria. Their locations are shown in Figure 1. The region is underlain by the Quaternary Chad Formation of the Yobe river basin system which consists of sands and clays, overlain by superficial aeolian and alluvial materials. Rainfall has a unimodal distribution with the rainy season starting in May/June, peaking in August and finishing in September/October. The remainder of the year is mainly dry. At Nguru (Figure 1) rainfall data are available from 1962-1997. The mean annual rainfall for the study period is 431 mm. For Maiduguri there is detailed field information for one rainy season including a study of soil water conditions and crop growth for experimental plots. It is assumed that the sandy soils and millet crop have the same properties and growing seasons at the two locations.

In section 5 the plausibility of the soil water balance calculations is assessed by comparing with field soil moisture records and with crop yields. In section 6 the sensitivities of the recharge estimates to possible variations in soil moisture balance parameters are examined.

Three important features of the model are particularly highlighted: *first*, the unmanageable complexities of multi-layer models (especially in a developing-country context) are rejected in favour of only the necessary level of complexity needed to adequately represent the physical processes involved. *Second*, to represent the early stages of crop growth in semi-arid areas when there is a substantial soil moisture deficit compared to the rooting depth a new feature is introduced, namely near surface storage, which represents water stored in the vicinity of the soil surface which is available for evapotranspiration on rainless days following major rainfall events. Third, in the absence of the possibility of validating the model using known values of deep drainage, model *plausibility* is evaluated, with reference to the physical credibility of the model, and to documented features of the soil-crop-water relationships in the region.

Further application of the model by one of the authors (Rushton) has led to it being used by the UK Environment Agency (Hulme et al, 2001) in a temperate climate; additional modifications are expected to allow its use in the humid tropics too. This versatility is viewed by the authors as a significant strength.

INCLUDE FIGURE 1 HERE

2. Key physical processes

When using a soil moisture balance to estimate deep drainage from the base of the soil zone there are certain key physical processes which must be represented.

2.1 Key physical processes: Figure 2(a) illustrates the principal hydrological processes associated with the soil zone during a specified period of time, which is usually selected as one day (Gee and Hillel 1988). Part of the rain falling on vegetation may be intercepted, and subsequently evaporate, making it unavailable for infiltration. It can be argued that in semi-arid locations the explicit estimation of interception is unnecessary, since actual evapotranspiration is water-limited rather than energy-limited. The water which is intercepted and evaporated is not subsequently available for transpiration, so the total of interception and transpiration is similar to what would be calculated as actual evapotranspiration if interception were ignored. Although Savenije (2004) argues, with some justification, that modellers should not ignore interception, our model makes no explicit allowance for it. Nevertheless, the inclusion of interception would be a simple modification were it considered appropriate.

When the rainfall reaches the ground surface it will enter the soil zone unless it exceeds the infiltration capacity. Water which does not enter the soil zone becomes runoff. The infiltrating water results in an increase in the water stored in the soil zone. From the soil zone, water is transpired by plants, water is drawn to the soil surface for evaporation and some water leaves from the base of the soil zone as deep drainage.

INCLUDE FIGURE 2 HERE

Figure 3 shows how crop conditions change with time. The diagram refers to a single crop grown during the rainy season. Before the crop is sown, bare soil evaporation is the only process occurring. After sowing, the roots extend and draw water from deeper in the soil store, transpiring it to the atmosphere. After harvest bare soil conditions apply once again. Three significant soil zone conditions are sketched in the lower half of Figure 3; they are each considered in more detail in Section 3.

INCLUDE FIGURE 3 HERE

2.2 Transpiration and water stress: transpiration is the process of water loss from vegetation; this requires the extraction of water by the root system. Transpiration is caused by the evaporative demand of the atmosphere through the process of vapour exchange between the leaves and air; it depends on a large number of climatic factors such as radiation, air temperature, air humidity and wind speed, which determine the pressure gradient between the plant tissues and the air. Different kinds of plants have different transpiration rates, depending on their number of stomata and other characteristics. However the availability of soil water and the ability of the roots to extract water from the soil are key factors which affect the actual transpiration rate (Allen et al. 1998). Although plant stomata respond not only to soil moisture deficits, but also to atmospheric conditions, in our model the crop is assumed to transpire at the potential rate when there is no limitation of soil water supply. As the soil water content decreases, the system comes under stress and the transpiration rate decreases. Transpiration ceases at the permanent wilting point.

2.3 Bare soil evaporation: the process of evaporation from a bare soil can be divided into three stages (Hillel 1998): (a) in the first stage the soil is wet and evaporation occurs at the potential rate, hence the only limitation is the atmospheric demand; (b) when the soil becomes dryer water cannot be supplied to the soil surface fast enough to meet the evaporative demand, and so the rate of evaporation decreases as the thickness of the dry layer increases; finally (c) the rate of evaporation becomes very small compared to the potential demand.

2.4 Sowing and seed germination: the distribution of soil moisture with depth and the timing and duration of early rainfall are critical for the sowing and successful germination of the seed. The retention of some water near to the soil surface, so that it is available for shallow roots during the period following sowing, is illustrated in Figure 4 which refers to non-irrigated millet crops planted in deep sandy soils at two sites in semi-arid Niger (Payne et al. 1991). The soil water content measured at eight or four days after sowing (*DAS*) shows an increased water content near the soil surface (approximately indicated by the shaded areas); this promotes seed germination. This increased water content in the vicinity of the soil surface is described by us as *Near Surface Storage* of water (*NSS*). The moisture content distributions at flowering and the maximum depths of the root zones are also shown in Figure 4. At Chikal the rainfall of only 196 mm constrains root development.

INCLUDE FIGURE 4 HERE

Near Surface Storage is also important when rainfall occurs during the dry season. The evaporation demand on that day is met by the rainfall. Even though the upper part of the soil profile is very dry, a proportion of the hydrologically effective rainfall (rainfall minus runoff and evaporation) is retained near the soil surface for evaporation on the following day(s).

2.5 Runoff: when the infiltration capacity of the soil is limited, runoff is likely to occur on days with significant rainfall. The intense rainfall events which occur in semi-arid areas often lead to considerable runoff (Eilers 2002). This is enhanced by surface crusts which form on sandy soils. Runoff from one location becomes run-on to a nearby area, from which infiltration, and potentially deep drainage, can occur. In our model this is not explicitly allowed for, although minor modifications to the computational model could easily be made to this effect.

2.6 Deep drainage: when the water content of the soil reaches field capacity, water can drain through the soil zone to become potential recharge. Field capacity is defined as the amount of water which the soil can hold against gravitational forces. At field capacity, any excess water drains through the soil zone. Although in practice a small amount of water can drain from the soil zone when the water content is slightly below field capacity, the assumption that recharge only occurs at field capacity leads to minor errors. Our model does not explicitly allow for by-pass or rapid flow through or from the soil zone. In many soils and environments such processes are important, and their inclusion could usefully represent a further development of our model.

2.7 Soil water content: the soil water content at the end of any given time step is computed by a simple mass balance applied to the soil zone. Inputs of water originate from infiltrated rainfall, while losses are due to (bare soil) evaporation, transpiration, and deep drainage. It is assumed that when the soil is too dry to sustain evaporation or transpiration (either because it has entered Hillel's third stage of evaporation, or because vegetation has died or been harvested), then no further water loss occurs. Consequently the soil water content at the beginning of the rainy season is the same as that at the end of the previous cropping season.

3. Inclusion of key physical features in a soil water balance

This section considers how the features, introduced in Section 2, are included in the conceptual and computational models of a daily soil water balance of land under a millet crop. Reference is made to the components of the soil water balance model of Figure 2(b) and to Figure 5 which presents a soil water balance for Nguru from mid April to late October 1995. The significance of Figure 5 is considered further in Section 4.

3.1. Soil Moisture Deficit

Moisture conditions in the soil are described using the soil moisture deficit *SMD* which is defined as the amount of water required to bring the soil up to field capacity. Components of the soil water balance, Fig 2(b), are the infiltration *In* which equals the daily rainfall *Pr* less runoff *RO* (estimation of the runoff is considered in Section 3.5). Potential evapotranspiration *PE* represents potential transpiration by the crop and/or evaporation from bare soil. The actual evapotranspiration *AE* depends on the current *SMD* and the infiltration *In* (Section 3.2). Any surplus $In - AE$ leads to a reduction in the *SMD*. Since the soil moisture deficit does not provide information about the distribution of moisture with depth, the concept of near surface storage is introduced to represent the retention of soil water near the surface (*NSS* is considered in Section 3.4). When the *SMD* becomes negative, deep drainage occurs from the bottom of the soil zone (Section 3.6).

3.2. Transpiration and water stress

The estimation of the potential evapotranspiration *PE* for a crop depends on the reference evapotranspiration *ETo,* which is calculated using the Penman-Monteith equation (Allen et al. 1998), multiplied by the crop coefficient K_C which represents the crop characteristics which differentiate the crop from the reference surface of grass (Abdulmumin and Misari 1990, Allen et al. 1998). The significance of K_C for a millet crop can be identified from Figure 5(b) which *shows ETo* as the full line and the daily *PE* by the unfilled bars. For most of the year the coefficient K_C is greater than 1.0 although it falls below 1.0 as the crop ripens and harvest is approached.

INCLUDE FIGURE 5 HERE

The depth of soil water which can be used by the crop, the Total Available Water *TAW*, depends on the rooting depth of the crop (see Figure 3) and on the moisture holding properties of the soil.

$$TAW = (\theta_{FC} - \theta_{WP}) Z_r \tag{1}$$

where θ_{FC} and θ_{WP} are the moisture contents at field capacity and wilting point and Z_r is the current depth of the roots. Consequently, during the growing season at Nguru *TAW* increases from 26 to 108 mm (Figure 5(c)). Moisture can be extracted by the roots without water stress when the soil moisture deficit does not exceed the Readily Available Water *RAW* which is estimated by multiplying *TAW* by a depletion factor *p*. Values of all the above parameters can be obtained from the FAO Report *Crop Evapotranspiration*, Allen et al. (1998). Figure 5(c) shows how *RAW* and *TAW* vary during a year. When the soil moisture deficit is greater than *RAW*, a water stress coefficient applies, Figure6, which leads to an actual evapotranspiration *AE* which may be less than *PE*. The equations used to calculate K_S and then *AE* are listed on the right of Figure 6. The equation in the box in Figure 6 indicates that when there is infiltration, but it is less than *PE*, this infiltration is collected by the shallow roots but the remaining evapotranspiration demand is met at a reduced rate calculated from the current K_S.

In Figure 5(b) the potential evapotranspiration is shown by the unshaded bars and the actual evapotranspiration by the black bars. Up to day 195, actual evapotranspiration occurs mainly on days with rainfall (or on the following days if *NSS* applies or *SMD* < *TAW*). After day 193 the growing roots ensure that some water is transpired. During the main rainy season, evapotranspiration is at the potential rate up to day 249 because *SMD* is less than *RAW*. Between days 250 and 276, provided that *In* < *PE*, actual evapotranspiration is less than the potential rate since *RAW* < *SMD* < *TAW*.

INCLUDE FIGURE 6 HERE

3.3. Bare soil evaporation

Bare soil evaporation occurs before and after the rainy season. It can be estimated by multiplying *ETo* by an evaporation coefficient K_E which, according to Allen et al. (1998), equals 1.05. Since K_C and K_E are usually slightly above unity, *PE* for the whole year, Figure 5(b), is just above *ETo* apart from the period immediately before harvest. When bare soil evaporation is predominant, the Readily Evaporable Water *REW* and the Total Evaporable Water *TEW* replace *RAW* and *TAW* where (Allen et al. 1998)

$$TEW = 1000\left(\theta_{FC} - 0.5\theta_{WP}\right)Z_e \qquad (2)$$

In this equation Z_e, the thickness of the surface soil layer which is subject to drying by evaporation, is set at 0.25 m. During the dry season *TEW* = 26 mm and *REW* = 16 mm. The variation throughout the year of *REW* or *RAW* and *TEW* or *TAW* is shown in Figure 5(c). Example (i) of Figure 3 illustrates the situation where no evaporation occurs because *SMD* > *TEW*.

3.4. Near Surface Storage

The concept of moisture stored near the surface of the soil on days of significant rainfall was introduced in Section 2 and sketched in example (ii) of Figure 3. The method of including this mechanism in a soil water balance calculation is illustrated in the schematic diagram of Figure 7. In Figure 7(a) the variation of the volumetric water content with depth at the start of a day is indicated by the broken line (which for depths greater than 0.8 m coincides with the full line). The full line represents the volumetric water content at the end of the day. The total shaded area shows the increase in water content which arises from a substantial infiltration minus the actual evapotranspiration; this quantity is the hydrologically effective rainfall, *HER*. A factor, *FrNSS* defines how *HER* is allocated between near surface storage and reducing the soil moisture deficit:

(i) $FrNSS \times HER$ is available for evapotranspiration by shallow roots (or evaporated from the soil surface) on the following days,

(ii) $(1.0 - FrNSS) \times HER$ is used to reduce the *SMD*.

INCLUDE FIGURE 7 HERE

To represent the cultivated Sahelian sandy soil of the study area and the associated land preparation to retain moisture near the soil surface, *FrNSS* is set at 0.45. For soils with higher clay contents, larger values are appropriate. The way in which *FrNSS* = 0.45 influences the actual evapotranspiration is shown in Table 1. Infiltration of 30 mm occurs on day 1 and a further infiltration of 6 mm on day 3. At the end of day 1 (30.0 – 6.0) mm is available; 45% is allocated to *NSS* with 55% used to reduce the *SMD*. This *NSS* of 10.8 mm ensures that evapotranspiration occurs at the potential rate of 5.8 mm on day 2; the remaining 5.0 mm is distributed between *NSS* and reducing the *SMD*. On day 3 the infiltration of 6.0 mm plus *NSS* of 2.3 mm means that *AE* = *PE* with 1.1 mm allocated to *NSS*. On day 4 the near surface storage of 1.1 mm is transpired directly with the remaining 4.9 mm of *PE* transpired at a reduced rate according to K_S as indicated in the footnote to Table 1.

The importance of near surface storage can be observed in Figure 5. On day 112 when the infiltration is 13.3 mm, *AE* = *PE* = 5.9 mm with the quantity in near surface storage *NSS* = 3.3 mm. On the following day this water is transpired. Heavy rainfall on day 183 results in infiltration of 32 mm. Near surface storage is significant on the two following days.

3.5. <u>Runoff</u>

On a plot scale, surface runoff depends on the surface characteristics (gradient, soil and vegetation), rainfall intensity and the antecedent soil moisture conditions. An approximate technique for estimating daily runoff is developed which uses parameters of the soil water balance, namely daily rainfall and antecedent soil moisture conditions (represented by the *SMD* at the start of the day), with a matrix of coefficients which is used to represent the runoff coefficients. The coefficients used for this study are recorded in Table 2. For a daily rainfall of 40 mm with the *SMD* = 20 mm, the runoff is $0.25 \times 40 = 10$ mm, but reduces to $0.10 \times 40 = 4$ mm/d when the *SMD* = 100 mm. For intermediate values of rainfall intensity and *SMD*, linear interpolation is used. For Nguru in 1995, Figure 5(a) indicates that the annual runoff totals 53 mm and exceeds 1.0 mm on six days. These runoff coefficients are devised to represent observed intensities of runoff. In the light of uncertainties about the coefficients, a sensitivity analysis should be carried out with a range of plausible values for the coefficients (see Section 6 example 4).

3.6. Deep Drainage

When, during a daily water balance calculation, the infiltration results in a negative value of the soil moisture deficit, the soil water content reaches field capacity. Consequently the soil becomes free draining, the negative *SMD* becomes potential recharge from the base of the soil zone and the *SMD* is set to zero, (see example (iii) of Figure 3). For Nguru in 1995, Figure 5(c) indicates that the *SMD* reduces rapidly early in the growing season and becomes negative due to the heavy rainfall on day 197 leading to a deep drainage of 7.1 mm as plotted in Figure 5(d). A small potential recharge of 1.7 mm also occurs on day 198. Due to the heavy rainfall on day 212 the *SMD* again becomes negative with deep drainage of 5.9 mm.

3.7. Suitability of the single store model

This paper presents a single soil water store with some water retained near to the soil surface on days with heavy rainfall. Other workers, for example Ragab et al. (1997), Finch (2001), Kendy et al. (2003) use multi-store (multiple soil layer) models. There are two main drawbacks to multi-store models: first, procedures are required to represent the transfer of water between the individual soil layers, and the distribution of transpiration from the layers. These procedures may fail to represent what actually happens in the field. For instance, field experiments show that different patterns of roots develop in different years (McGowan et al.

1984) hence a predetermined depth distribution for the withdrawal of water by the roots may be invalid. The second drawback is that a great deal of data is required, which is often not available, at least in the contexts for which the present model was designed.

Although the model presented in this paper also implicitly includes a (maximum) rooting depth which is assumed to be achieved every year (a model aspect which could be modified relatively easily if so desired), the model makes no assumptions about the depth distribution of water uptake by roots. It is also economical in terms of data requirements. The authors believe that the single store soil water balance with near surface storage adequately represents all the important physical processes when the purpose of the water balance model is to estimate deep drainage from a cropped area.

4. Typical and long-term results for Nguru

Soil water balance calculations are carried out for Nguru where rainfall data are available from 1962-1997. The mean annual rainfall for the study period is 431 mm. In the absence of daily agrometeorological data (except rainfall), the daily reference evapotranspiration values are derived by linear disaggregation from long-term monthly means calculated using the Penman-Monteith equation. The maximum value of K_C for millet is 1.1, the soil evaporation coefficient K_E is 1.05. These and other parameter values are summarised in Table 3. The soil properties for the sandy soil are field capacity of 0.12 m^3/m^3 and permanent wilting point of 0.03 m^3/m^3; these values are consistent with the field values determined by Grema and Hess (1994) in North-east Nigeria and Rockström et al. (1998) in semi-arid Niger. They lie within the range of values suggested in FAO 56 (Allen et al. 1998) for a sandy soil. The total available water *TAW* and the total evaporable water *TEW* are calculated from these soil properties (see Eqs 1 and 2). A linear root growth is assumed, Figure 3, to a maximum effective rooting depth of 1.2 m. *REW* and *RAW* are calculated using a depletion factor p

equal to 0.6 (Rockström et al. 1998). The maximum depth from which evaporation can occur is 0.25 m. Variations of *TAW* or *TEW* and *RAW* or *REW* with time are plotted in Figure 5(c).

4.1. Planting date

In semi-arid areas, the establishment of successful rainfed crops depends on the adjustment of the growth cycle to the seasonal distribution of rainfall. A farmer may take the risk and plant at the first rainfall but it may be necessary to re-plant again if a dry spell follows. Mortimore (1989), in a study of five villages in Northeast Nigeria, reports that on average three millet plantings were necessary during the dry year of 1975. Several authors have defined criteria for the *onset of rains* when planting can take place. These are summarised in Table 4. Each of these methods has been tested in water balance calculations over 36 years for Nguru; they lead to a significant variation in the estimated date for the *onset of rains*. The methods of Stern et al (1982) and Sivakumar (1992) are too stringent, predicting that for some years the *onset of rains* would never occur. On the other hand, the methods of Benoit (1977) and Agnew (1991) do not identify the frequent occurrence of dry spells in the days following the first rains. Although the method of Kowal and Kassam (1978) is based on rainfall for ten-day periods, in most years their method provides a realistic planting date. Therefore the approach adopted was to use the criteria of Kowal and Kassam (1978) and after an initial simulation, manually adjust the planting date when necessary to be consistent with observed agricultural practices.

4.2. Detailed results for 1995

Each year has distinctive features. 1995 has been selected to illustrate soil water balance calculations. The annual rainfall of 384 mm with 36 rainy days is below the annual average of 431 mm. However, the *SMD* at start of the rainy season of 26 mm is unusually small, occurring as it does because of the high rainfall in 1994. For most years the *SMD* at the onset of the rainy season exceeds 100 mm. Inputs to the soil moisture balance are the daily rainfall, the daily potential evapotranspiration deduced from monthly estimates and the variation of *RAW* or *REW* and *TAW* or *TEW* throughout the year.

Figure 5(a) shows the rainfall with runoff plotted below the horizontal axis. Calculated runoff totals 53 mm. Consequently, of the total rainfall of 384 mm, only 331 mm infiltrated into the soil to contribute to the soil water balance.

Diagram (b) of Figure 5 shows the potential evapotranspiration as unfilled bars and the calculated actual evapotranspiration as filled bars. Before the start of the rainy season and after the end of the rainy season there were few days when rainfall occurred; the resulting infiltration was quickly evaporated as indicated by filled bars. At other times during the dry season the evaporation was zero. On the other hand, during much of the rainy season the actual evapotranspiration was at the potential rate. Even on days with zero rainfall, when the *SMD* was less than *RAW* the crop was not under stress and could draw sufficient water from the soil store. After day 249 when the *SMD* became greater than *RAW*, evapotranspiration occurred at below the potential rate apart from days with substantial rainfall. The decreasing *AE* in the days approaching harvest had little effect on the crop yield. The fact that actual evapotranspiration during the *initial*, *develop* and *mid* stages of the crop growth was at or close to the potential rate, resulted in a reasonable crop yield despite an *annual AE* of only 393 mm when the *annual PE* was 1849 mm. The first and final days on which deep drainage occurred, days 197 and 212, were early in the rainy season, this timing arose from the unusually small soil moisture deficit at the start of the rainy season.

Soil moisture deficits hardly changed during the dry season; any rainfall which occurred was evaporated rapidly. At the end of the rainy season after harvest on day 277 the *SMD* was 104.5 mm. It remains at this value until the rainy season of 1996. The contrast between the soil moisture deficits for the dry seasons 1994-95 and 1995-96 demonstrates the importance of representing adequately the soil water conditions during the dry season.

4.3. Deep drainage estimates for 1962 to 1997

The relationship between calculated annual potential recharge and the annual rainfall for Nguru for the thirty-six years from 1962 to 1997 is presented in Figure 8. Potential recharge varies substantially from year to year depending on the distribution, intensity and frequency of rainfall events and especially on the soil moisture deficit from the preceding dry season. During the 36 years, annual potential recharge varies from zero to 95 mm with twenty-three years having zero. The mean annual potential recharge is 14.1 mm. The highest annual rainfall, which resulted in zero potential recharge, was 650 mm in 1963; the *SMD* at the start of the year was 98 mm, there was substantial rainfall before and after the cropping season. This contrasts markedly with 1995 when rainfall of 384 mm resulted in a potential recharge of 15 mm because the *SMD* at the start of the rainy season was only 26 mm. The high value of modelled potential recharge in 1977 occurred because significant rainfall after harvest in 1976 meant that the soil moisture deficit at the start of the 1977 rainy season was only moderate. Furthermore, although the rainfall in 1977 was not unusually high (1.18 times the mean annual rainfall), the distribution of rainfall resulted in a zero soil moisture deficit on six occasions, leading to an annual potential recharge of 95mm. Finally, Figure 8 demonstrates that in semi-arid areas annual rainfall totals are not a good predictor of annual potential recharge.

INCLUDE FIGURE 8 HERE

5. Plausibility

Having developed a soil water balance model for estimating deep drainage, the credibility of the results generated by the model needs to be considered. In locations where groundwater has been exploited for many years, the potential recharge estimates can be incorporated in a regional groundwater model; comparisons between the predicted and actual groundwater head hydrographs test the adequacy of the recharge estimates (Kavalanekar et al. 1992, Rushton 2003). However, for the present study where field data were limited, and there were no absolute reference values of deep drainage available for calibration and validation, the concept of *plausibility* was used to assess the adequacy of the soil water balance model (Carter et al. 2002). The concept of plausibility includes judgments about the structure of the model as well as tests of the model results. It assumes that if the model is reasonable in representing the complex hydrological system, then it will be able to compute a credible water balance. This procedure is not limited to an analysis of the deep drainage component alone but also considers additional outputs which can help to assess the credibility of the representation of soil-water by the water balance model. Of several alternative plausibility approaches explored by Eilers (2002), two are discussed below. Both relate to rainfed millet cropped land to which the model has been applied in sections 3 and 4 of this paper.

5.1. Experimental field trial at Maiduguri

Comparisons are made between field measurements of soil moisture content in a cropped plot at the University of Maiduguri, Nigeria (Grema and Hess 1994), with results from the soil water balance model. During a field trial in 1992, estimates of the variation of moisture content with depth were obtained from neutron probe readings at 20 cm intervals below ground surface. From these moisture content estimates, the total soil moisture to a depth of 1.3 m is calculated. The filled diamonds in Figure 9 represent these field estimates. Due to the limited precision of the experimental technique and changes in soil moisture close to the soil surface following rainfall, sudden changes between individual estimates do occur.

INCLUDE FIGURE 9 HERE

So that comparisons can be made with values of *SMD* from the model, the average of the field values for 24th August, 1st, 8th and 15th September of approximately 162 mm is assumed to represent the maximum total soil moisture content. Taking this value as corresponding to field capacity (*SMD* = 0), an alternative vertical axis is provided on the right of the diagram to represent soil moisture deficits. Estimated soil moisture deficits from the water balance calculations are plotted on Figure 9 as a continuous line. Approximate agreement occurs between the total moisture content deduced from field readings and the soil moisture deficits calculated from the water balance model. The differences of up to 20 mm arise due to lack of precision in the soil moisture measurements and approximations inherent in the soil water balance approach.

5.2. Dagaceri

An indirect method of verifying the credibility of the soil water balance model is based on field observations which contain valuable information about the physical system in the semi-arid region of North-east Nigeria, Mortimore (1989). Mortimore presents a diary for the years 1972-1985 in the life of the small village of Dagaceri (see Figure 1) from which a range of information was gathered about rainfall and crop yield for each crop season. The author gives a brief narrative for each year in which he describes the overall crop yield and its relation to the rainfall patterns. As Dagaceri is geographically not far from Nguru (approximately 30 km Southwest) and the rainfall patterns and crop characteristics are similar, selected outputs from the water balance model using the daily climatic data from Nguru, are compared with field observations at Dagaceri. Since the model estimates the daily actual evapotranspiration, this information can be used to infer crop survival and overall crop yields.

Figure 10 is devised to summarise the results of the soil water balance calculations; the two axes in the diagram refer to:

- *x axis* number of days during crop development stage when *SMD* > *RAW*. High values should correspond to poor yields.
- *y axis* ratio *AE*/*PE* during crop growing season. High values should correspond to good yields.

Years are identified by the following symbols: + years with a satisfactory millet crop, × years with unsatisfactory yields and Δ years with other factors influencing the yield. Years with a good yield, +, are all found towards the top-left of the diagram; poor yields, ×, are towards the bottom-right. This qualitative analysis suggests that, apart from years when additional factors operate, the soil water balance model reasonably represent the physical mechanisms which affect the millet crop yield.

INCLUDE FIGURE 10 HERE

6. Sensitivity

Preliminary investigations were carried out into the sensitivity of the model's outputs to uncertainties which may arise from (a) empirical errors in the field measurements and (b) parameter variation as a result of spatial variability. The variability is assessed by running the model for the maximum and minimum values of the range of variation of single parameters. The range of variation of parameters is based on values from literature especially Allen et al. (1998) and field observations. The analysis refers to a sandy soil planted with a millet crop using the entire thirty-six year rainfall dataset from Nguru. Variations in five parameters are considered. The findings, which are summarised in Figure 11, are discussed below. The first two refer to changes in crop properties, the third to different soil properties, the fourth to a change in runoff coefficients and the final variation refers to the fraction of water stored near the soil surface.

INCLUDE FIGURE 11 HERE

Variation in the mid season crop coefficient: the potential evapotranspiration for the crop is calculated by multiplying the reference crop evapotranspiration by the crop coefficient. Increasing and decreasing the coefficient by 0.1 leads to a maximum value of $K_C = 1.2$ and a minimum of 1.0. In practice it is unlikely that the crop coefficient would lie outside this range. The resultant mean deep drainage estimates are 11.2 mm/year (due to higher evapotranspiration losses) and 17.8 mm/year compared to 14.1 mm/year for the standard parameters.

Variation in the maximum depth of roots: due to a number of factors including the ability of the roots to grow deeper during seasons with limited rainfall, the maximum rooting depth can vary within the range 1.2 ± 0.25 m. With the greater rooting depth and hence higher values of *TAW*, the actual evapotranspiration is higher with a mean potential recharge of 10.8 mm/year. Reduced root penetration results in a potential recharge of 18.5 mm.

Increases and decreases in the difference between moisture contents at field capacity and at wilting point: these alterations lead to the greatest changes in recharge, Figure 11. Due to variations in the grain sizes in the soil, the difference $\theta_{WP} - \theta_{FC} = 0.09 \pm 0.02$ can occur in practice; this leads to actual evapotranspiration estimates of 383 and 363 mm/year and potential recharge estimates of 9.5 and 21.8 mm/year.

Modifications to runoff coefficients: the runoff coefficients of Table 2 are devised to represent runoff but they are only approximate estimates. Consequently increasing each of the coefficients by 20% or decreasing by 20% are appropriate variations. They lead to a decrease in the estimated deep drainage to 10.7 mm/year and an increase to 17.8 mm/year. These changes highlight the need to obtain realistic field estimates of the runoff.

Fraction of water stored near the soil surface: the coefficient *FrNSS* is an empirical coefficient which lies between zero and 1.0. The value of 0.45 which is used in the simulations is selected to represent the retention of water near the soil surface during the early stages of crop growth. It is unlikely that *FrNSS* is less than 0.2 or greater than 0.7; these values are used in the sensitivity analysis and lead to estimated recharges of 15.2 and 13.3 mm/year. These results refer to the overall potential recharge averaged over a thirty-six year period. Often near surface storage is significant during the early stages of crop growth or during the dry season, but this does not result in a substantial change in the potential recharge (which for many years is zero).

This sensitivity analysis indicates that the two single parameters which cause greatest changes to deep drainage estimates are the difference between moisture contents at field capacity and wilting point, and the effective depth of the roots. Due to the variability of these parameters in the field, uncertainties do occur in potential recharge estimates for semi-arid areas.

7. Conclusions

7.1 General conclusion

Recharge estimation in semi-arid areas is required to assess the availability of groundwater for domestic, agricultural and industrial use. For routine deep drainage or potential recharge estimates the soil water balance technique is appropriate provided that the physical processes in the soil and the crop are adequately represented, with realistic parameter values, in the calculations. In the absence of the possibility of true calibration and validation, the plausibility of this approach has been confirmed by comparisons with field measurements of soil moisture conditions and crop yields.

In this paper deep drainage is estimated from a single store soil water balance in which potential recharge only occurs when the soil moisture deficit becomes zero and the soil becomes free draining. The validity of this assumption is questioned by Kendy et al. (2003). Their study relates to an irrigated cropland in the North China Plain. Their calibrated model, which represents unsaturated conditions in a soil consisting of several layers, predicts that drainage occurs from the lowest layer on most days throughout the simulation period of three years. There are two differences from the conditions in the Nguru study area. First, the growing seasons of the two irrigated crops in the North China Plain extend over most of the year with substantial irrigation of similar magnitude to the annual rainfall. Consequently the soil moisture deficit is relatively small for most of the time. However for the rainfed crop at Nguru the soil moisture deficit only reduces to small values following significant rainfall events. Second, field studies in the North China Plain indicate that towards the bottom of the soil profile there is a 45 cm layer of clay loam with a saturated hydraulic conductivity of 0.003 m/d; this clay loam layer delays the downward movement of water. In Nguru, the soil is sandy so that water can move down freely through the soil profile when field capacity is reached. Consequently the assumption of a free draining soil is acceptable. Nevertheless, the study of Kendy et al. (2003) demonstrates that slow drainage may occur if the soil contains a substantial low permeability layer; the soil water balance model described in this paper requires modification if the soil profile contains low permeability layers.

7.2 Conclusions regarding the model

The model presented here includes the main processes which determine deep drainage. In using a single soil water store (single layer), the model has avoided the inclusion of unnecessary and inadequately understood complexities – specifically the detailed manner in which soil and roots interact to redistribute and take up water. It has also avoided the necessity of having detailed layer-wise soil and root data, which rarely exist in practice.

Aspects of the model which could usefully be further developed include:

- the explicit inclusion of interception;
- response of the crop to stress imposed by atmospheric conditions;
- the inclusion of run-on from adjacent areas;
- the linking of root development to soil moisture deficit;
- the inclusion of bypass flow.

The next logical step in model development would be to adapt it for area-wide estimates of potential recharge, taking account of spatial variability of soil and crop properties.

In addition to the semi-arid application described in this paper, the model has also been applied in a temperate climate (Hulme et al, 2001), and work is on-going to apply it in the humid tropics. The model has so far only been used under rainfed cropping conditions, but irrigated crops can also be included by setting the daily rainfall equal to the actual rainfall plus the depth of irrigation.

7.3 Application of the model to semi-arid North- East Nigeria

Recharge estimates based on a thirty-six year rainfall record at Nguru in North-east Nigeria indicate that the recharge cannot be related directly to the annual rainfall. A very important factor influencing the recharge is the soil moisture deficit at the start of the rainy season. This deficit varies a great deal from year to year, as a function of the timing and amount of late rains in the days and weeks prior to harvest. The model assumes that once the crop is harvested, water can only be lost upwards by bare soil evaporation (until the top 25-50cm of soil is dry and Hillel's third stage of evaporation is reached), or downwards by deep drainage (in the unlikely event that the soil is still wetter than field capacity). Once the soil surface is dry, and a deficit exists in the lower part of the soil zone, the remaining water is effectively "frozen" in place until the next rainy season.

A study of the detailed water balances indicates that deep drainage is predicted to occur under rainfed millet cropping at Nguru when:

(i) the soil moisture deficit carried over from the previous year is less than 31 mm (for the case study used in this paper, total available water *TAW* is taken as 108 mm at full rooting depth);

(ii) there is a period with substantial rainfall with at least 240 mm during a period of 30 days (cf mean annual rainfall of 431 mm for Nguru).

There are two years when neither of the above criteria were met. However, concentrated rainfall of 127 mm in 5 days or 124 mm in two consecutive days resulted in the reduction of the soil moisture deficit to zero and the occurrence of deep drainage.

Sensitivity analyses show that recharge estimates are principally sensitive to the rooting depth and the total available water. The latter depends both on the rooting depth and water holding capacity. Although estimates of soil moisture contents at field capacity and wilting point are generally available (for example Allen et al. 1998), estimating the effective rooting depth is open to more uncertainty. In this study the same variation in rooting depth is assumed to occur each year, although in practice rooting depths are likely to vary from year to year. Consequently, sensitivity analyses should always be carried out to obtain a range of potential recharge estimates.

The problem of validation of the model remains. In the absence of known values of recharge, calibration and validation in the strict sense are not possible. Apart from the plausibility tests applied in this paper, the best that can be done is to compare model outputs with alternative models or with field-based estimation techniques. The model outputs presented in this paper are consistent with the field results of Edmunds et al (2002). Their work, carried out in the same part of Nigeria, using the chloride profiling technique at six field sites, estimated deep drainage of 20-76mm.a^{-1}, or after modification of rainfall chloride concentrations to fit a long-term rainfall chloride calibration model, 16-30mm. a^{-1}.

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A Single Layer Soil Water Balance Model for Estimating Deep Drainage (Potential Recharge): an Application to Cropped Land in Semi-Arid North-East Nigeria

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Abstract

The understanding and quantification of groundwater recharge in semi-arid areas is fundamental to sound management of water resources in such areas. A soil water balance model, if designed to adequately represent the physical processes involved, and if carried out with a short enough (daily) time step, can provide realistic estimates of deep drainage (potential recharge) over long periods.

We describe a single store (single layer) mass water balance model applicable to semi-arid areas, which recognises the wetting of the near-surface during rainfall, with subsequent availability of water for evaporation and transpiration in the days following rainfall. The model allows for the major hydrological processes taking place at or near the soil-vegetation surface including runoff.

Model results are presented for north-east Nigeria, for a continuous period of 36 years during which mean annual rainfall was 431mm (range 321-650mm) and mean annual modelled deep drainage was 14mm (range 0-95mm, with 23 years having zero potential recharge). The modelling results indicate that annual rainfall totals are not the main predictor of annual recharge. The temporal distribution of daily rainfall and the magnitude of the antecedent (pre-season) soil moisture deficit are the strongest determinants of deep drainage at a particular location, in a particular year. Sensitivity analysis of soil and vegetation parameters

suggests that deep drainage is most sensitive to water holding capacity and rooting depth. These are key parameters which determine spatial variability of potential recharge.

The model is shown to be plausible by examination of the concepts which underlie it, by comparison with field soil-moisture measurements, and by the model's ability to represent qualitative observations of crop yield variations from year to year.

Future development of the model could include applications to other climatic conditions and the inclusion of other hydrologic processes.

Keywords: Deep drainage, Potential recharge; Evapotranspiration; Nigeria; Semi-arid; Soil water balance.

1. Introduction

In semi-arid areas, the question of whether and under what conditions groundwater recharge occurs, and its magnitude, are fundamental to the management of water resources. Questions of spatial and temporal variability, as a function of soil, vegetation, and weather properties, are also basic to the understanding of the hydrology of such regions.

Estimating deep drainage (also referred to in this paper as potential recharge) in semi-arid environments is difficult for several reasons. First, the re-distribution of rainfall by the runoff process, and consequent localisation of infiltration and deep drainage would lead to a high degree of spatial variability of deep drainage, even were there no spatial variations in soil and vegetation properties. When soil and vegetation variations are considered too, the problem of spatial variability is compounded.

Second, the re-distribution of infiltrated rainfall in the soil profile, and its uptake by roots of crops and natural vegetation are complex processes. Our ability to adequately represent these subtle processes in multi-layered soil models incorporating assumptions about root-water uptake is so far rather limited. We suggest here that a modified single store (single layer) soil water balance model which makes few assumptions about the depth from which roots prefer to extract water, can adequately represent the processes involved, and provide reliable estimates of groundwater recharge under cropped land in semi-arid areas.

Third, in semi-arid environments the estimation of deep drainage is challenging because the potential evapotranspiration is invariably much larger than the rainfall. Consequently doubts have been expressed about the suitability of the soil water balance technique. Hendrickx and Walker (1997) consider that soil moisture budgeting models are of limited use since they are prone to large errors in recharge rates. This is a valid criticism when the model fails to represent soil and crop conditions, or uses too long a time step. The longer the time step, the greater the numerical similarity between infiltration and actual evapotranspiration, and hence the smaller the difference (deep drainage) between the two, and consequently the greater the possible error.

Field experiments for quantifying deep drainage, such as the use of natural or artificial tracers (eg chloride) or consideration of the movement of water in the unsaturated soil zone (Hendrickx and Walker 1997; Edmunds et al, 2002), provide valuable insights into the recharge processes but they are not suitable for routine estimation of potential recharge over large areas, or over long time periods. The soil water balance method is an alternative approach. If it provides a reliable representation of conditions for the crop and the soil, acceptable potential recharge estimates can be obtained.

A detailed review of alternative methods of estimating recharge, including soil water balance models, is provided by Kendy et al. (2003). An early example of potential recharge estimation in North-eastern Jordan using a soil water balance (Lloyd et al. 1967) demonstrates the viability of this approach.

Soil water balances are used widely in hydrological studies, but they vary in their features because the components included in the balance depend on the objectives of the study. Water balance methods are widely used for estimating crop water requirements in semi-arid areas as described in the FAO Irrigation and Drainage Paper 56, Crop Evapotranspiration (Allen et al. 1998). The methods described in that report are based on extensive field experience.

In order for the methods described by Allen et al (1998), and by us, to be used for regional potential recharge estimates, further work is needed on the appropriate lumping or discretisation of soil and vegetation properties over large areas with mixed bare soil, crop cover, and sparse shallow- and deep-rooting natural vegetation.

The conceptual and computational models described in this paper are intended for point estimates of deep drainage where daily rainfall records are available together with information about the reference crop potential evapotranspiration. From information about the soil, the crop and bare soil evaporation, estimates are made of the actual evapotranspiration throughout the year. No unnecessary complexities are included in the methodology.

The paper first presents (in section 2) the individual physical processes which together contribute to the conceptual model of the changing conditions in the soil and crop. These form the basis for the soil water balance calculations (presented in section 3, and applied there to Nguru, one of two sites in North-East Nigeria – see below). The conceptual and computational models must reflect the relevant properties of the soil, the nature of the crop, the growth of roots, the potential evapotranspiration from both the crop and from bare soil, the reduced evapotranspiration due to limited moisture availability and the conditions under which recharge can occur.

Section 4 of the paper further discusses the application of the model to Nguru and Maiduguri, two sites approximately 300km apart in semi-arid North-East Nigeria. Their locations are shown in Figure 1. The region is underlain by the Quaternary Chad Formation of the Yobe river basin system which consists of sands and clays, overlain by superficial aeolian and alluvial materials. Rainfall has a unimodal distribution with the rainy season starting in May/June, peaking in August and finishing in September/October. The remainder of the year is mainly dry. At Nguru (Figure 1) rainfall data are available from 1962-1997. The mean annual rainfall for the study period is 431 mm. For Maiduguri there is detailed field information for one rainy season including a study of soil water conditions and crop growth for experimental plots. It is assumed that the sandy soils and millet crop have the same properties and growing seasons at the two locations.

In section 5 the plausibility of the soil water balance calculations is assessed by comparing with field soil moisture records and with crop yields. In section 6 the sensitivities of the recharge estimates to possible variations in soil moisture balance parameters are examined.

Three important features of the model are particularly highlighted: *first*, the unmanageable complexities of multi-layer models (especially in a developing-country context) are rejected in favour of only the necessary level of complexity needed to adequately represent the physical processes involved. *Second*, to represent the early stages of crop growth in semi-arid areas when there is a substantial soil moisture deficit compared to the rooting depth a new feature is introduced, namely near surface storage, which represents water stored in the vicinity of the soil surface which is available for evapotranspiration on rainless days following major rainfall events. Third, in the absence of the possibility of validating the model using known values of deep drainage, model *plausibility* is evaluated, with reference to the physical credibility of the model, and to documented features of the soil-crop-water relationships in the region.

Further application of the model by one of the authors (Rushton) has led to it being used by the UK Environment Agency (Hulme et al, 2001) in a temperate climate; additional modifications are expected to allow its use in the humid tropics too. This versatility is viewed by the authors as a significant strength.

INCLUDE FIGURE 1 HERE

2. Key physical processes

When using a soil moisture balance to estimate deep drainage from the base of the soil zone there are certain key physical processes which must be represented.

2.1 Key physical processes: Figure 2(a) illustrates the principal hydrological processes associated with the soil zone during a specified period of time, which is usually selected as one day (Gee and Hillel 1988). Part of the rain falling on vegetation may be intercepted, and subsequently evaporate, making it unavailable for infiltration. It can be argued that in semi-arid locations the explicit estimation of interception is unnecessary, since actual evapotranspiration is water-limited rather than energy-limited. The water which is intercepted and evaporated is not subsequently available for transpiration, so the total of interception and transpiration is similar to what would be calculated as actual evapotranspiration if interception were ignored. Although Savenije (2004) argues, with some justification, that modellers should not ignore interception, our model makes no explicit allowance for it. Nevertheless, the inclusion of interception would be a simple modification were it considered appropriate.

When the rainfall reaches the ground surface it will enter the soil zone unless it exceeds the infiltration capacity. Water which does not enter the soil zone becomes runoff. The infiltrating water results in an increase in the water stored in the soil zone. From the soil zone, water is transpired by plants, water is drawn to the soil surface for evaporation and some water leaves from the base of the soil zone as deep drainage.

INCLUDE FIGURE 2 HERE

Figure 3 shows how crop conditions change with time. The diagram refers to a single crop grown during the rainy season. Before the crop is sown, bare soil evaporation is the only process occurring. After sowing, the roots extend and draw water from deeper in the soil store, transpiring it to the atmosphere. After harvest bare soil conditions apply once again. Three significant soil zone conditions are sketched in the lower half of Figure 3; they are each considered in more detail in Section 3.

INCLUDE FIGURE 3 HERE

2.2 Transpiration and water stress: transpiration is the process of water loss from vegetation; this requires the extraction of water by the root system. Transpiration is caused by the evaporative demand of the atmosphere through the process of vapour exchange between the leaves and air; it depends on a large number of climatic factors such as radiation, air temperature, air humidity and wind speed, which determine the pressure gradient between the plant tissues and the air. Different kinds of plants have different transpiration rates, depending on their number of stomata and other characteristics. However the availability of soil water and the ability of the roots to extract water from the soil are key factors which affect the actual transpiration rate (Allen et al. 1998). Although plant stomata respond not only to soil moisture deficits, but also to atmospheric conditions, in our model the crop is assumed to transpire at the potential rate when there is no limitation of soil water supply. As the soil water content decreases, the system comes under stress and the transpiration rate decreases. Transpiration ceases at the permanent wilting point.

2.3 Bare soil evaporation: the process of evaporation from a bare soil can be divided into three stages (Hillel 1998): (a) in the first stage the soil is wet and evaporation occurs at the potential rate, hence the only limitation is the atmospheric demand; (b) when the soil becomes dryer water cannot be supplied to the soil surface fast enough to meet the evaporative demand, and so the rate of evaporation decreases as the thickness of the dry layer increases; finally (c) the rate of evaporation becomes very small compared to the potential demand.

2.4 Sowing and seed germination: the distribution of soil moisture with depth and the timing and duration of early rainfall are critical for the sowing and successful germination of the seed. The retention of some water near to the soil surface, so that it is available for shallow roots during the period following sowing, is illustrated in Figure 4 which refers to non-irrigated millet crops planted in deep sandy soils at two sites in semi-arid Niger (Payne et al. 1991). The soil water content measured at eight or four days after sowing (*DAS*) shows an increased water content near the soil surface (approximately indicated by the shaded areas); this promotes seed germination. This increased water content in the vicinity of the soil surface is described by us as *Near Surface Storage* of water (*NSS*). The moisture content distributions at flowering and the maximum depths of the root zones are also shown in Figure 4. At Chikal the rainfall of only 196 mm constrains root development.

INCLUDE FIGURE 4 HERE

Near Surface Storage is also important when rainfall occurs during the dry season. The evaporation demand on that day is met by the rainfall. Even though the upper part of the soil profile is very dry, a proportion of the hydrologically effective rainfall (rainfall minus runoff and evaporation) is retained near the soil surface for evaporation on the following day(s).

2.5 Runoff: when the infiltration capacity of the soil is limited, runoff is likely to occur on days with significant rainfall. The intense rainfall events which occur in semi-arid areas often lead to considerable runoff (Eilers 2002). This is enhanced by surface crusts which form on sandy soils. Runoff from one location becomes run-on to a nearby area, from which infiltration, and potentially deep drainage, can occur. In our model this is not explicitly allowed for, although minor modifications to the computational model could easily be made to this effect.

2.6 Deep drainage: when the water content of the soil reaches field capacity, water can drain through the soil zone to become potential recharge. Field capacity is defined as the amount of water which the soil can hold against gravitational forces. At field capacity, any excess water drains through the soil zone. Although in practice a small amount of water can drain from the soil zone when the water content is slightly below field capacity, the assumption that recharge only occurs at field capacity leads to minor errors. Our model does not explicitly allow for by-pass or rapid flow through or from the soil zone. In many soils and environments such processes are important, and their inclusion could usefully represent a further development of our model.

2.7 Soil water content: the soil water content at the end of any given time step is computed by a simple mass balance applied to the soil zone. Inputs of water originate from infiltrated rainfall, while losses are due to (bare soil) evaporation, transpiration, and deep drainage. It is assumed that when the soil is too dry to sustain evaporation or transpiration (either because it has entered Hillel's third stage of evaporation, or because vegetation has died or been harvested), then no further water loss occurs. Consequently the soil water content at the beginning of the rainy season is the same as that at the end of the previous cropping season.

3. Inclusion of key physical features in a soil water balance

This section considers how the features, introduced in Section 2, are included in the conceptual and computational models of a daily soil water balance of land under a millet crop. Reference is made to the components of the soil water balance model of Figure 2(b) and to Figure 5 which presents a soil water balance for Nguru from mid April to late October 1995. The significance of Figure 5 is considered further in Section 4.

3.1. Soil Moisture Deficit

Moisture conditions in the soil are described using the soil moisture deficit *SMD* which is defined as the amount of water required to bring the soil up to field capacity. Components of the soil water balance, Fig 2(b), are the infiltration *In* which equals the daily rainfall *Pr* less runoff *RO* (estimation of the runoff is considered in Section 3.5). Potential evapotranspiration *PE* represents potential transpiration by the crop and/or evaporation from bare soil. The actual evapotranspiration *AE* depends on the current *SMD* and the infiltration *In* (Section 3.2). Any surplus $In - AE$ leads to a reduction in the *SMD*. Since the soil moisture deficit does not provide information about the distribution of moisture with depth, the concept of near surface storage is introduced to represent the retention of soil water near the surface (*NSS* is considered in Section 3.4). When the *SMD* becomes negative, deep drainage occurs from the bottom of the soil zone (Section 3.6).

3.2. Transpiration and water stress

The estimation of the potential evapotranspiration *PE* for a crop depends on the reference evapotranspiration *ETo,* which is calculated using the Penman-Monteith equation (Allen et al. 1998), multiplied by the crop coefficient K_C which represents the crop characteristics which differentiate the crop from the reference surface of grass (Abdulmumin and Misari 1990, Allen et al. 1998). The significance of K_C for a millet crop can be identified from Figure 5(b) which *shows ETo* as the full line and the daily *PE* by the unfilled bars. For most of the year the coefficient K_C is greater than 1.0 although it falls below 1.0 as the crop ripens and harvest is approached.

INCLUDE FIGURE 5 HERE

The depth of soil water which can be used by the crop, the Total Available Water *TAW*, depends on the rooting depth of the crop (see Figure 3) and on the moisture holding properties of the soil.

$$TAW = (\theta_{FC} - \theta_{WP}) Z_r \tag{1}$$

where θ_{FC} and θ_{WP} are the moisture contents at field capacity and wilting point and Z_r is the current depth of the roots. Consequently, during the growing season at Nguru *TAW* increases from 26 to 108 mm (Figure 5(c)). Moisture can be extracted by the roots without water stress when the soil moisture deficit does not exceed the Readily Available Water *RAW* which is estimated by multiplying *TAW* by a depletion factor *p*. Values of all the above parameters can be obtained from the FAO Report *Crop Evapotranspiration*, Allen et al. (1998). Figure 5(c) shows how *RAW* and *TAW* vary during a year. When the soil moisture deficit is greater than *RAW*, a water stress coefficient applies, Figure6, which leads to an actual evapotranspiration *AE* which may be less than *PE*. The equations used to calculate K_S and then *AE* are listed on the right of Figure 6. The equation in the box in Figure 6 indicates that when there is infiltration, but it is less than *PE*, this infiltration is collected by the shallow roots but the remaining evapotranspiration demand is met at a reduced rate calculated from the current K_S.

In Figure 5(b) the potential evapotranspiration is shown by the unshaded bars and the actual evapotranspiration by the black bars. Up to day 195, actual evapotranspiration occurs mainly on days with rainfall (or on the following days if *NSS* applies or *SMD* < *TAW*). After day 193 the growing roots ensure that some water is transpired. During the main rainy season, evapotranspiration is at the potential rate up to day 249 because *SMD* is less than *RAW*. Between days 250 and 276, provided that *In* < *PE*, actual evapotranspiration is less than the potential rate since *RAW* < *SMD* < *TAW*.

INCLUDE FIGURE 6 HERE

3.3. Bare soil evaporation

Bare soil evaporation occurs before and after the rainy season. It can be estimated by multiplying *ETo* by an evaporation coefficient K_E which, according to Allen et al. (1998), equals 1.05. Since K_C and K_E are usually slightly above unity, *PE* for the whole year, Figure 5(b), is just above *ETo* apart from the period immediately before harvest. When bare soil evaporation is predominant, the Readily Evaporable Water *REW* and the Total Evaporable Water *TEW* replace *RAW* and *TAW* where (Allen et al. 1998)

$$TEW = 1000\left(\theta_{FC} - 0.5\theta_{WP}\right)Z_e \tag{2}$$

In this equation Z_e, the thickness of the surface soil layer which is subject to drying by evaporation, is set at 0.25 m. During the dry season *TEW* = 26 mm and *REW* = 16 mm. The variation throughout the year of *REW* or *RAW* and *TEW* or *TAW* is shown in Figure 5(c). Example (i) of Figure 3 illustrates the situation where no evaporation occurs because *SMD* > *TEW*.

3.4. Near Surface Storage

The concept of moisture stored near the surface of the soil on days of significant rainfall was introduced in Section 2 and sketched in example (ii) of Figure 3. The method of including this mechanism in a soil water balance calculation is illustrated in the schematic diagram of Figure 7. In Figure 7(a) the variation of the volumetric water content with depth at the start of a day is indicated by the broken line (which for depths greater than 0.8 m coincides with the full line). The full line represents the volumetric water content at the end of the day. The total shaded area shows the increase in water content which arises from a substantial infiltration minus the actual evapotranspiration; this quantity is the hydrologically effective rainfall, *HER*. A factor, *FrNSS* defines how *HER* is allocated between near surface storage and reducing the soil moisture deficit:

(i) $FrNSS \times HER$ is available for evapotranspiration by shallow roots (or evaporated from the soil surface) on the following days,

(ii) $(1.0 - FrNSS) \times HER$ is used to reduce the *SMD*.

INCLUDE FIGURE 7 HERE

To represent the cultivated Sahelian sandy soil of the study area and the associated land preparation to retain moisture near the soil surface, *FrNSS* is set at 0.45. For soils with higher clay contents, larger values are appropriate. The way in which *FrNSS* = 0.45 influences the actual evapotranspiration is shown in Table 1. Infiltration of 30 mm occurs on day 1 and a further infiltration of 6 mm on day 3. At the end of day 1 (30.0 – 6.0) mm is available; 45% is allocated to *NSS* with 55% used to reduce the *SMD*. This *NSS* of 10.8 mm ensures that evapotranspiration occurs at the potential rate of 5.8 mm on day 2; the remaining 5.0 mm is distributed between *NSS* and reducing the *SMD*. On day 3 the infiltration of 6.0 mm plus *NSS* of 2.3 mm means that *AE* = *PE* with 1.1 mm allocated to *NSS*. On day 4 the near surface storage of 1.1 mm is transpired directly with the remaining 4.9 mm of *PE* transpired at a reduced rate according to K_S as indicated in the footnote to Table 1.

The importance of near surface storage can be observed in Figure 5. On day 112 when the infiltration is 13.3 mm, *AE* = *PE* = 5.9 mm with the quantity in near surface storage *NSS* = 3.3 mm. On the following day this water is transpired. Heavy rainfall on day 183 results in infiltration of 32 mm. Near surface storage is significant on the two following days.

3.5. <u>Runoff</u>

On a plot scale, surface runoff depends on the surface characteristics (gradient, soil and vegetation), rainfall intensity and the antecedent soil moisture conditions. An approximate technique for estimating daily runoff is developed which uses parameters of the soil water balance, namely daily rainfall and antecedent soil moisture conditions (represented by the *SMD* at the start of the day), with a matrix of coefficients which is used to represent the runoff coefficients. The coefficients used for this study are recorded in Table 2. For a daily rainfall of 40 mm with the *SMD* = 20 mm, the runoff is $0.25 \times 40 = 10$ mm, but reduces to $0.10 \times 40 = 4$ mm/d when the *SMD* = 100 mm. For intermediate values of rainfall intensity and *SMD*, linear interpolation is used. For Nguru in 1995, Figure 5(a) indicates that the annual runoff totals 53 mm and exceeds 1.0 mm on six days. These runoff coefficients are devised to represent observed intensities of runoff. In the light of uncertainties about the coefficients, a sensitivity analysis should be carried out with a range of plausible values for the coefficients (see Section 6 example 4).

3.6. Deep Drainage

When, during a daily water balance calculation, the infiltration results in a negative value of the soil moisture deficit, the soil water content reaches field capacity. Consequently the soil becomes free draining, the negative *SMD* becomes potential recharge from the base of the soil zone and the *SMD* is set to zero, (see example (iii) of Figure 3). For Nguru in 1995, Figure 5(c) indicates that the *SMD* reduces rapidly early in the growing season and becomes negative due to the heavy rainfall on day 197 leading to a deep drainage of 7.1 mm as plotted in Figure 5(d). A small potential recharge of 1.7 mm also occurs on day 198. Due to the heavy rainfall on day 212 the *SMD* again becomes negative with deep drainage of 5.9 mm.

3.7. Suitability of the single store model

This paper presents a single soil water store with some water retained near to the soil surface on days with heavy rainfall. Other workers, for example Ragab et al. (1997), Finch (2001), Kendy et al. (2003) use multi-store (multiple soil layer) models. There are two main drawbacks to multi-store models: first, procedures are required to represent the transfer of water between the individual soil layers, and the distribution of transpiration from the layers. These procedures may fail to represent what actually happens in the field. For instance, field experiments show that different patterns of roots develop in different years (McGowan et al.

1984) hence a predetermined depth distribution for the withdrawal of water by the roots may be invalid. The second drawback is that a great deal of data is required, which is often not available, at least in the contexts for which the present model was designed.

Although the model presented in this paper also implicitly includes a (maximum) rooting depth which is assumed to be achieved every year (a model aspect which could be modified relatively easily if so desired), the model makes no assumptions about the depth distribution of water uptake by roots. It is also economical in terms of data requirements. The authors believe that the single store soil water balance with near surface storage adequately represents all the important physical processes when the purpose of the water balance model is to estimate deep drainage from a cropped area.

4. Typical and long-term results for Nguru

Soil water balance calculations are carried out for Nguru where rainfall data are available from 1962-1997. The mean annual rainfall for the study period is 431 mm. In the absence of daily agrometeorological data (except rainfall), the daily reference evapotranspiration values are derived by linear disaggregation from long-term monthly means calculated using the Penman-Monteith equation. The maximum value of K_C for millet is 1.1, the soil evaporation coefficient K_E is 1.05. These and other parameter values are summarised in Table 3. The soil properties for the sandy soil are field capacity of 0.12 m^3/m^3 and permanent wilting point of 0.03 m^3/m^3; these values are consistent with the field values determined by Grema and Hess (1994) in North-east Nigeria and Rockström et al. (1998) in semi-arid Niger. They lie within the range of values suggested in FAO 56 (Allen et al. 1998) for a sandy soil. The total available water *TAW* and the total evaporable water *TEW* are calculated from these soil properties (see Eqs 1 and 2). A linear root growth is assumed, Figure 3, to a maximum effective rooting depth of 1.2 m. *REW* and *RAW* are calculated using a depletion factor p

equal to 0.6 (Rockström et al. 1998). The maximum depth from which evaporation can occur is 0.25 m. Variations of *TAW* or *TEW* and *RAW* or *REW* with time are plotted in Figure 5(c).

4.1. Planting date

In semi-arid areas, the establishment of successful rainfed crops depends on the adjustment of the growth cycle to the seasonal distribution of rainfall. A farmer may take the risk and plant at the first rainfall but it may be necessary to re-plant again if a dry spell follows. Mortimore (1989), in a study of five villages in Northeast Nigeria, reports that on average three millet plantings were necessary during the dry year of 1975. Several authors have defined criteria for the *onset of rains* when planting can take place. These are summarised in Table 4. Each of these methods has been tested in water balance calculations over 36 years for Nguru; they lead to a significant variation in the estimated date for the *onset of rains*. The methods of Stern et al (1982) and Sivakumar (1992) are too stringent, predicting that for some years the *onset of rains* would never occur. On the other hand, the methods of Benoit (1977) and Agnew (1991) do not identify the frequent occurrence of dry spells in the days following the first rains. Although the method of Kowal and Kassam (1978) is based on rainfall for ten-day periods, in most years their method provides a realistic planting date. Therefore the approach adopted was to use the criteria of Kowal and Kassam (1978) and after an initial simulation, manually adjust the planting date when necessary to be consistent with observed agricultural practices.

4.2. Detailed results for 1995

Each year has distinctive features. 1995 has been selected to illustrate soil water balance calculations. The annual rainfall of 384 mm with 36 rainy days is below the annual average of 431 mm. However, the *SMD* at start of the rainy season of 26 mm is unusually small, occurring as it does because of the high rainfall in 1994. For most years the *SMD* at the onset of the rainy season exceeds 100 mm. Inputs to the soil moisture balance are the daily rainfall, the daily potential evapotranspiration deduced from monthly estimates and the variation of *RAW* or *REW* and *TAW* or *TEW* throughout the year.

Figure 5(a) shows the rainfall with runoff plotted below the horizontal axis. Calculated runoff totals 53 mm. Consequently, of the total rainfall of 384 mm, only 331 mm infiltrated into the soil to contribute to the soil water balance.

Diagram (b) of Figure 5 shows the potential evapotranspiration as unfilled bars and the calculated actual evapotranspiration as filled bars. Before the start of the rainy season and after the end of the rainy season there were few days when rainfall occurred; the resulting infiltration was quickly evaporated as indicated by filled bars. At other times during the dry season the evaporation was zero. On the other hand, during much of the rainy season the actual evapotranspiration was at the potential rate. Even on days with zero rainfall, when the *SMD* was less than *RAW* the crop was not under stress and could draw sufficient water from the soil store. After day 249 when the *SMD* became greater than *RAW*, evapotranspiration occurred at below the potential rate apart from days with substantial rainfall. The decreasing *AE* in the days approaching harvest had little effect on the crop yield. The fact that actual evapotranspiration during the *initial*, *develop* and *mid* stages of the crop growth was at or close to the potential rate, resulted in a reasonable crop yield despite an *annual AE* of only 393 mm when the *annual PE* was 1849 mm. The first and final days on which deep drainage occurred, days 197 and 212, were early in the rainy season, this timing arose from the unusually small soil moisture deficit at the start of the rainy season.

Soil moisture deficits hardly changed during the dry season; any rainfall which occurred was evaporated rapidly. At the end of the rainy season after harvest on day 277 the *SMD* was 104.5 mm. It remains at this value until the rainy season of 1996. The contrast between the soil moisture deficits for the dry seasons 1994-95 and 1995-96 demonstrates the importance of representing adequately the soil water conditions during the dry season.

4.3. Deep drainage estimates for 1962 to 1997

The relationship between calculated annual potential recharge and the annual rainfall for Nguru for the thirty-six years from 1962 to 1997 is presented in Figure 8. Potential recharge varies substantially from year to year depending on the distribution, intensity and frequency of rainfall events and especially on the soil moisture deficit from the preceding dry season. During the 36 years, annual potential recharge varies from zero to 95 mm with twenty-three years having zero. The mean annual potential recharge is 14.1 mm. The highest annual rainfall, which resulted in zero potential recharge, was 650 mm in 1963; the *SMD* at the start of the year was 98 mm, there was substantial rainfall before and after the cropping season. This contrasts markedly with 1995 when rainfall of 384 mm resulted in a potential recharge of 15 mm because the *SMD* at the start of the rainy season was only 26 mm. The high value of modelled potential recharge in 1977 occurred because significant rainfall after harvest in 1976 meant that the soil moisture deficit at the start of the 1977 rainy season was only moderate. Furthermore, although the rainfall in 1977 was not unusually high (1.18 times the mean annual rainfall), the distribution of rainfall resulted in a zero soil moisture deficit on six occasions, leading to an annual potential recharge of 95mm. Finally, Figure 8 demonstrates that in semi-arid areas annual rainfall totals are not a good predictor of annual potential recharge.

INCLUDE FIGURE 8 HERE

5. Plausibility

Having developed a soil water balance model for estimating deep drainage, the credibility of the results generated by the model needs to be considered. In locations where groundwater has been exploited for many years, the potential recharge estimates can be incorporated in a regional groundwater model; comparisons between the predicted and actual groundwater head hydrographs test the adequacy of the recharge estimates (Kavalanekar et al. 1992, Rushton 2003). However, for the present study where field data were limited, and there were no absolute reference values of deep drainage available for calibration and validation, the concept of *plausibility* was used to assess the adequacy of the soil water balance model (Carter et al. 2002). The concept of plausibility includes judgments about the structure of the model as well as tests of the model results. It assumes that if the model is reasonable in representing the complex hydrological system, then it will be able to compute a credible water balance. This procedure is not limited to an analysis of the deep drainage component alone but also considers additional outputs which can help to assess the credibility of the representation of soil-water by the water balance model. Of several alternative plausibility approaches explored by Eilers (2002), two are discussed below. Both relate to rainfed millet cropped land to which the model has been applied in sections 3 and 4 of this paper.

5.1. Experimental field trial at Maiduguri

Comparisons are made between field measurements of soil moisture content in a cropped plot at the University of Maiduguri, Nigeria (Grema and Hess 1994), with results from the soil water balance model. During a field trial in 1992, estimates of the variation of moisture content with depth were obtained from neutron probe readings at 20 cm intervals below ground surface. From these moisture content estimates, the total soil moisture to a depth of 1.3 m is calculated. The filled diamonds in Figure 9 represent these field estimates. Due to the limited precision of the experimental technique and changes in soil moisture close to the soil surface following rainfall, sudden changes between individual estimates do occur.

INCLUDE FIGURE 9 HERE

So that comparisons can be made with values of *SMD* from the model, the average of the field values for 24th August, 1st, 8th and 15th September of approximately 162 mm is assumed to represent the maximum total soil moisture content. Taking this value as corresponding to field capacity (*SMD* = 0), an alternative vertical axis is provided on the right of the diagram to represent soil moisture deficits. Estimated soil moisture deficits from the water balance calculations are plotted on Figure 9 as a continuous line. Approximate agreement occurs between the total moisture content deduced from field readings and the soil moisture deficits calculated from the water balance model. The differences of up to 20 mm arise due to lack of precision in the soil moisture measurements and approximations inherent in the soil water balance approach.

5.2. Dagaceri

An indirect method of verifying the credibility of the soil water balance model is based on field observations which contain valuable information about the physical system in the semi-arid region of North-east Nigeria, Mortimore (1989). Mortimore presents a diary for the years 1972-1985 in the life of the small village of Dagaceri (see Figure 1) from which a range of information was gathered about rainfall and crop yield for each crop season. The author gives a brief narrative for each year in which he describes the overall crop yield and its relation to the rainfall patterns. As Dagaceri is geographically not far from Nguru (approximately 30 km Southwest) and the rainfall patterns and crop characteristics are similar, selected outputs from the water balance model using the daily climatic data from Nguru, are compared with field observations at Dagaceri. Since the model estimates the daily actual evapotranspiration, this information can be used to infer crop survival and overall crop yields.

Figure 10 is devised to summarise the results of the soil water balance calculations; the two axes in the diagram refer to:

- *x axis* number of days during crop development stage when $SMD > RAW$. High values should correspond to poor yields.
- *y axis* ratio AE/PE during crop growing season. High values should correspond to good yields.

Years are identified by the following symbols: + years with a satisfactory millet crop, × years with unsatisfactory yields and Δ years with other factors influencing the yield. Years with a good yield, +, are all found towards the top-left of the diagram; poor yields, ×, are towards the bottom-right. This qualitative analysis suggests that, apart from years when additional factors operate, the soil water balance model reasonably represent the physical mechanisms which affect the millet crop yield.

INCLUDE FIGURE 10 HERE

6. Sensitivity

Preliminary investigations were carried out into the sensitivity of the model's outputs to uncertainties which may arise from (a) empirical errors in the field measurements and (b) parameter variation as a result of spatial variability. The variability is assessed by running the model for the maximum and minimum values of the range of variation of single parameters. The range of variation of parameters is based on values from literature especially Allen et al. (1998) and field observations. The analysis refers to a sandy soil planted with a millet crop using the entire thirty-six year rainfall dataset from Nguru. Variations in five parameters are considered. The findings, which are summarised in Figure 11, are discussed below. The first two refer to changes in crop properties, the third to different soil properties, the fourth to a change in runoff coefficients and the final variation refers to the fraction of water stored near the soil surface.

INCLUDE FIGURE 11 HERE

<u>Variation in the mid season crop coefficient</u>: the potential evapotranspiration for the crop is calculated by multiplying the reference crop evapotranspiration by the crop coefficient. Increasing and decreasing the coefficient by 0.1 leads to a maximum value of K_C = 1.2 and a minimum of 1.0. In practice it is unlikely that the crop coefficient would lie outside this

range. The resultant mean deep drainage estimates are 11.2 mm/year (due to higher evapotranspiration losses) and 17.8 mm/year compared to 14.1 mm/year for the standard parameters.

Variation in the maximum depth of roots: due to a number of factors including the ability of the roots to grow deeper during seasons with limited rainfall, the maximum rooting depth can vary within the range 1.2 ± 0.25 m. With the greater rooting depth and hence higher values of *TAW*, the actual evapotranspiration is higher with a mean potential recharge of 10.8 mm/year. Reduced root penetration results in a potential recharge of 18.5 mm.

Increases and decreases in the difference between moisture contents at field capacity and at wilting point: these alterations lead to the greatest changes in recharge, Figure 11. Due to variations in the grain sizes in the soil, the difference $\theta_{WP} - \theta_{FC} = 0.09 \pm 0.02$ can occur in practice; this leads to actual evapotranspiration estimates of 383 and 363 mm/year and potential recharge estimates of 9.5 and 21.8 mm/year.

Modifications to runoff coefficients: the runoff coefficients of Table 2 are devised to represent runoff but they are only approximate estimates. Consequently increasing each of the coefficients by 20% or decreasing by 20% are appropriate variations. They lead to a decrease in the estimated deep drainage to 10.7 mm/year and an increase to 17.8 mm/year. These changes highlight the need to obtain realistic field estimates of the runoff.

Fraction of water stored near the soil surface: the coefficient *FrNSS* is an empirical coefficient which lies between zero and 1.0. The value of 0.45 which is used in the simulations is selected to represent the retention of water near the soil surface during the early stages of crop growth. It is unlikely that *FrNSS* is less than 0.2 or greater than 0.7; these values are used in the sensitivity analysis and lead to estimated recharges of 15.2 and 13.3 mm/year. These results refer to the overall potential recharge averaged over a thirty-six year period. Often near surface storage is significant during the early stages of crop growth or during the dry season, but this does not result in a substantial change in the potential recharge (which for many years is zero).

This sensitivity analysis indicates that the two single parameters which cause greatest changes to deep drainage estimates are the difference between moisture contents at field capacity and wilting point, and the effective depth of the roots. Due to the variability of these parameters in the field, uncertainties do occur in potential recharge estimates for semi-arid areas.

7. Conclusions

7.1 General conclusion

Recharge estimation in semi-arid areas is required to assess the availability of groundwater for domestic, agricultural and industrial use. For routine deep drainage or potential recharge estimates the soil water balance technique is appropriate provided that the physical processes in the soil and the crop are adequately represented, with realistic parameter values, in the calculations. In the absence of the possibility of true calibration and validation, the plausibility of this approach has been confirmed by comparisons with field measurements of soil moisture conditions and crop yields.

In this paper deep drainage is estimated from a single store soil water balance in which potential recharge only occurs when the soil moisture deficit becomes zero and the soil becomes free draining. The validity of this assumption is questioned by Kendy et al. (2003). Their study relates to an irrigated cropland in the North China Plain. Their calibrated model, which represents unsaturated conditions in a soil consisting of several layers, predicts that drainage occurs from the lowest layer on most days throughout the simulation period of three years. There are two differences from the conditions in the Nguru study area. First, the growing seasons of the two irrigated crops in the North China Plain extend over most of the year with substantial irrigation of similar magnitude to the annual rainfall. Consequently the soil moisture deficit is relatively small for most of the time. However for the rainfed crop at Nguru the soil moisture deficit only reduces to small values following significant rainfall events. Second, field studies in the North China Plain indicate that towards the bottom of the soil profile there is a 45 cm layer of clay loam with a saturated hydraulic conductivity of 0.003 m/d; this clay loam layer delays the downward movement of water. In Nguru, the soil is sandy so that water can move down freely through the soil profile when field capacity is reached. Consequently the assumption of a free draining soil is acceptable. Nevertheless, the study of Kendy et al. (2003) demonstrates that slow drainage may occur if the soil contains a substantial low permeability layer; the soil water balance model described in this paper requires modification if the soil profile contains low permeability layers.

7.2 Conclusions regarding the model

The model presented here includes the main processes which determine deep drainage. In using a single soil water store (single layer), the model has avoided the inclusion of unnecessary and inadequately understood complexities – specifically the detailed manner in which soil and roots interact to redistribute and take up water. It has also avoided the necessity of having detailed layer-wise soil and root data, which rarely exist in practice.

Aspects of the model which could usefully be further developed include:

- the explicit inclusion of interception;
- response of the crop to stress imposed by atmospheric conditions;
- the inclusion of run-on from adjacent areas;
- the linking of root development to soil moisture deficit;
- the inclusion of bypass flow.

The next logical step in model development would be to adapt it for area-wide estimates of potential recharge, taking account of spatial variability of soil and crop properties.

In addition to the semi-arid application described in this paper, the model has also been applied in a temperate climate (Hulme et al, 2001), and work is on-going to apply it in the humid tropics. The model has so far only been used under rainfed cropping conditions, but irrigated crops can also be included by setting the daily rainfall equal to the actual rainfall plus the depth of irrigation.

7.3 Application of the model to semi-arid North- East Nigeria

Recharge estimates based on a thirty-six year rainfall record at Nguru in North-east Nigeria indicate that the recharge cannot be related directly to the annual rainfall. A very important factor influencing the recharge is the soil moisture deficit at the start of the rainy season. This deficit varies a great deal from year to year, as a function of the timing and amount of late rains in the days and weeks prior to harvest. The model assumes that once the crop is harvested, water can only be lost upwards by bare soil evaporation (until the top 25-50cm of soil is dry and Hillel's third stage of evaporation is reached), or downwards by deep drainage (in the unlikely event that the soil is still wetter than field capacity). Once the soil surface is dry, and a deficit exists in the lower part of the soil zone, the remaining water is effectively "frozen" in place until the next rainy season.

A study of the detailed water balances indicates that deep drainage is predicted to occur under rainfed millet cropping at Nguru when:

(i) the soil moisture deficit carried over from the previous year is less than 31 mm (for the case study used in this paper, total available water *TAW* is taken as 108 mm at full rooting depth);

(ii) there is a period with substantial rainfall with at least 240 mm during a period of 30 days (cf mean annual rainfall of 431 mm for Nguru).

There are two years when neither of the above criteria were met. However, concentrated rainfall of 127 mm in 5 days or 124 mm in two consecutive days resulted in the reduction of the soil moisture deficit to zero and the occurrence of deep drainage.

Sensitivity analyses show that recharge estimates are principally sensitive to the rooting depth and the total available water. The latter depends both on the rooting depth and water holding capacity. Although estimates of soil moisture contents at field capacity and wilting point are generally available (for example Allen et al. 1998), estimating the effective rooting depth is open to more uncertainty. In this study the same variation in rooting depth is assumed to occur each year, although in practice rooting depths are likely to vary from year to year. Consequently, sensitivity analyses should always be carried out to obtain a range of potential recharge estimates.

The problem of validation of the model remains. In the absence of known values of recharge, calibration and validation in the strict sense are not possible. Apart from the plausibility tests applied in this paper, the best that can be done is to compare model outputs with alternative models or with field-based estimation techniques. The model outputs presented in this paper are consistent with the field results of Edmunds et al (2002). Their work, carried out in the same part of Nigeria, using the chloride profiling technique at six field sites, estimated deep drainage of 20-76mm.a^{-1}, or after modification of rainfall chloride concentrations to fit a long-term rainfall chloride calibration model, 16-30mm. a^{-1}.

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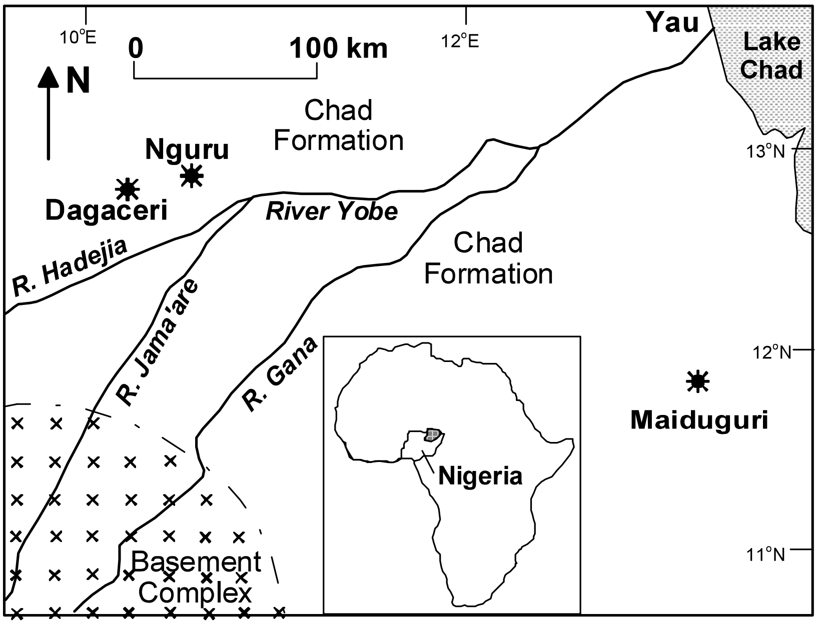
Figure 1



10°E
12°E
0
100 km
N
Yau
Lake Chad
13°N
12°N
11°N
Chad Formation
Nguru
Dagaceri
River Yobe
R. Hadejia
R. Jama'are
R. Gana
Chad Formation
Maiduguri
Nigeria
Basement Complex

Figure 2

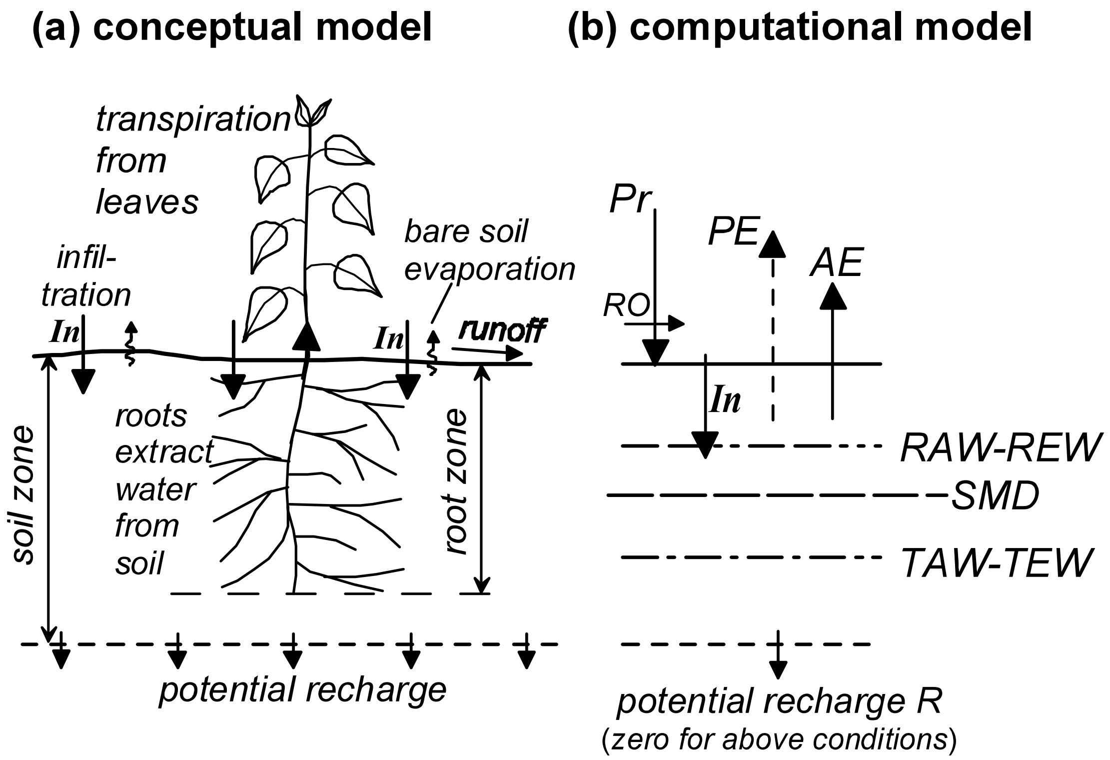
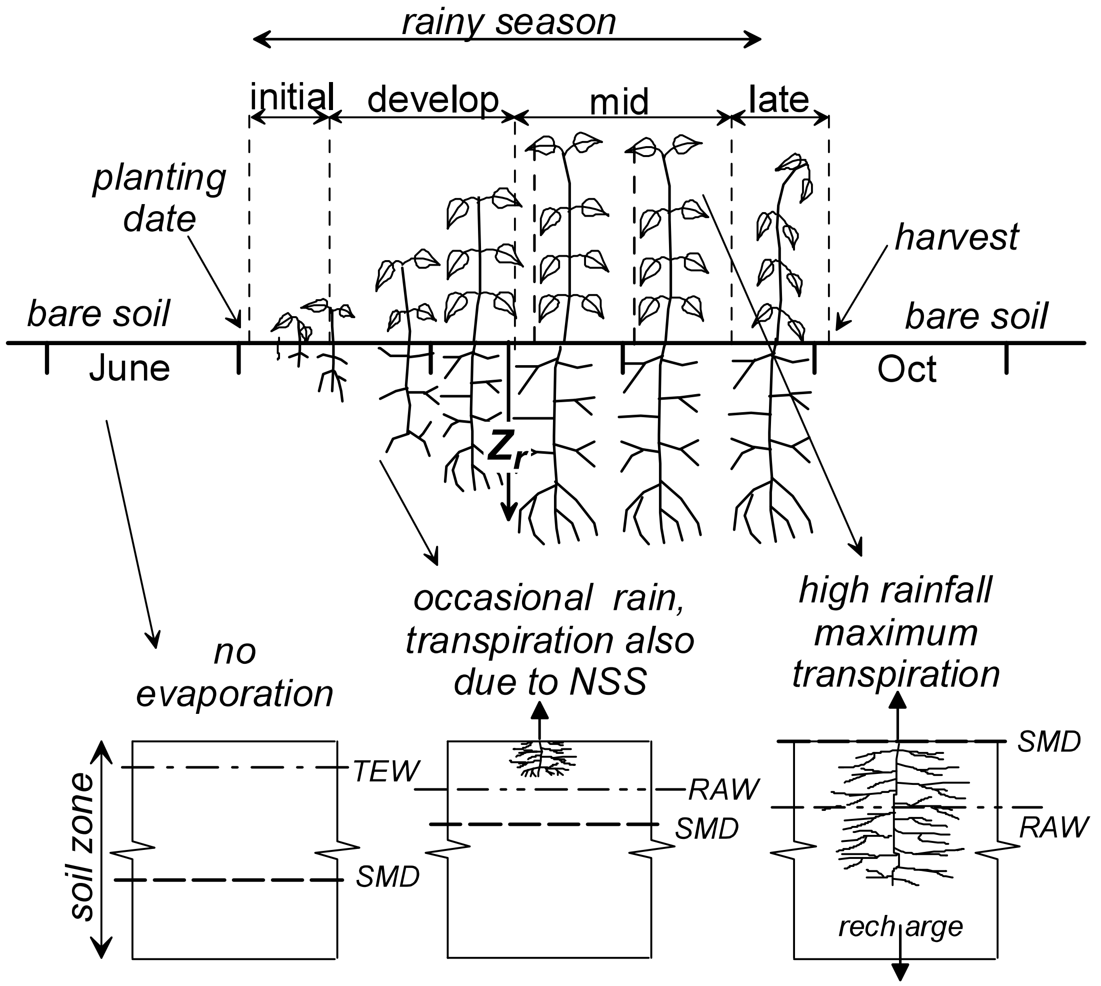

(a) conceptual model
(b) computational model
transpiration from leaves
bare soil evaporation
infil-tration
In
In
runoff
roots extract water from soil
soil zone
root zone
potential recharge
Pr
PE
AE
RO
In
RAW-REW
SMD
TAW-TEW
potential recharge R
(zero for above conditions)

Figure 3



(i) bare soil conditions before rainfall

(ii) initial stage of crop early in rainy season

(iii) crop mid-season, if *SMD* is negative potential recharge occurs

Figure 4

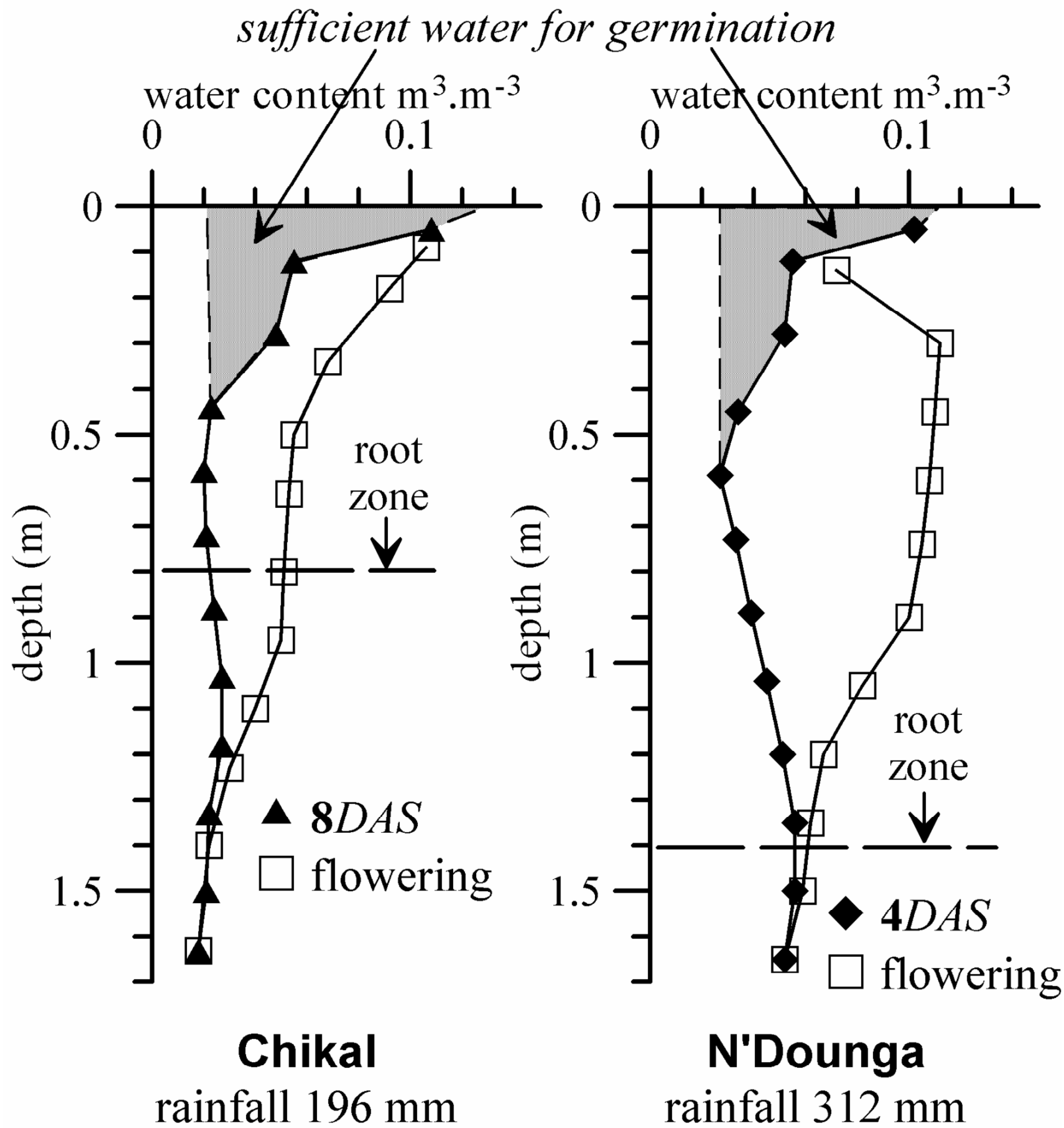

sufficient water for germination
water content m3.m-3
0
0.1
0
0.5
1
1.5
depth (m)
root
zone
▲ 8DAS
□ flowering
Chikal
rainfall 196 mm
water content m3.m-3
0
0.1
0
0.5
1
1.5
depth (m)
root
zone
◆ 4DAS
□ flowering
N'Dounga
rainfall 312 mm

Figure 5

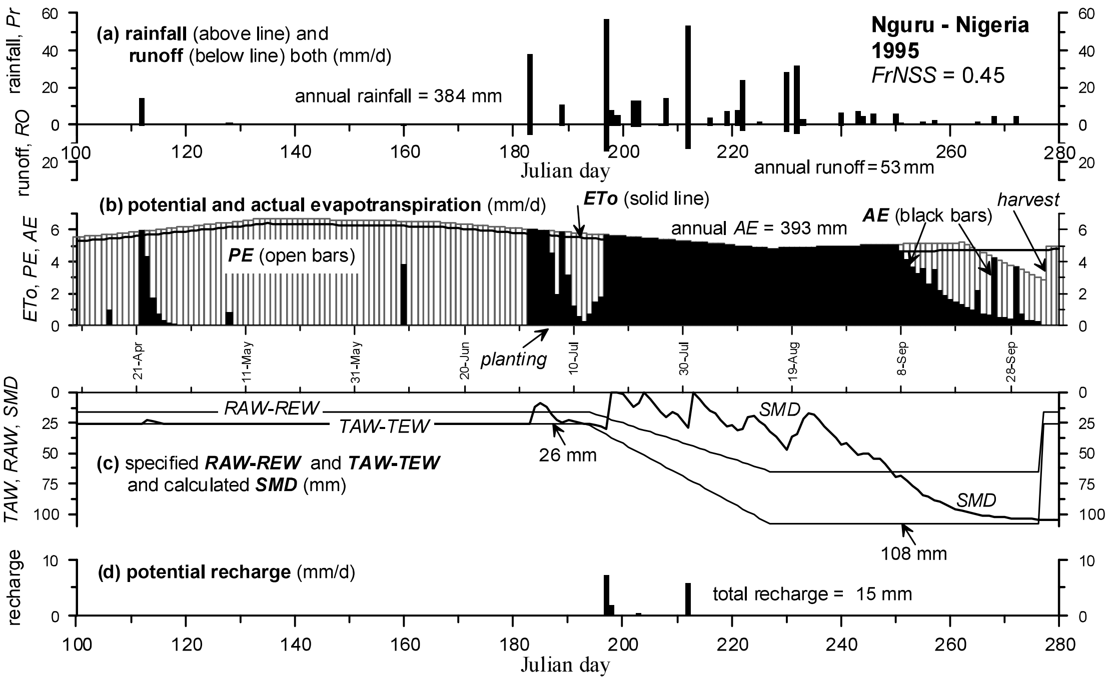
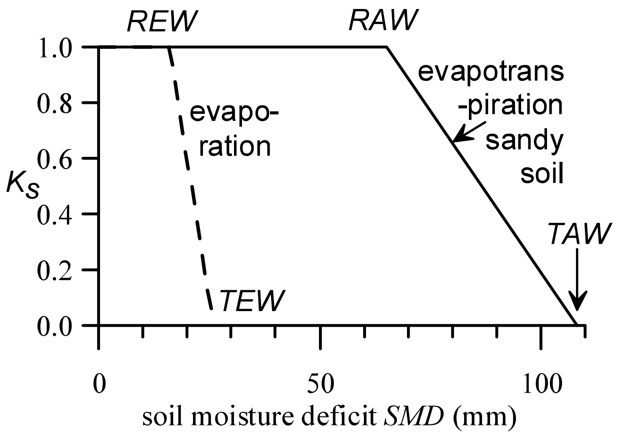

Nguru - Nigeria
1995
FrNSS = 0.45
(a) rainfall (above line) and
runoff (below line) both (mm/d)
annual rainfall = 384 mm
annual runoff = 53 mm
rainfall, Pr
runoff, RO
Julian day
(b) potential and actual evapotranspiration (mm/d)
ETo (solid line)
annual AE = 393 mm
AE (black bars)
harvest
PE (open bars)
planting
ETo, PE, AE
21-Apr
11-May
31-May
20-Jun
10-Jul
30-Jul
19-Aug
8-Sep
28-Sep
RAW-REW
TAW-TEW
SMD
26 mm
108 mm
(c) specified RAW-REW and TAW-TEW
and calculated SMD (mm)
TAW, RAW, SMD
(d) potential recharge (mm/d)
total recharge = 15 mm
recharge
Julian day

Figure 6



$TAW = 1000\,(\theta_{FC} - \theta_{WP})$

$RAW = p\ TAW$

$K_s = 1.0$ when $SMD < RAW$

$K_s = 0.0$ when $SMD > TAW$

For $RAW < SMD < TAW$

$$K_s = \frac{TAW - SMD}{TAW - RAW}$$

when infiltration $In > PE$:

$AE = PE$

$$\boxed{\begin{array}{l}\text{when infiltration } In < PE \\ AE = In + K_s\,(PE - In)\end{array}}$$

Figure 7

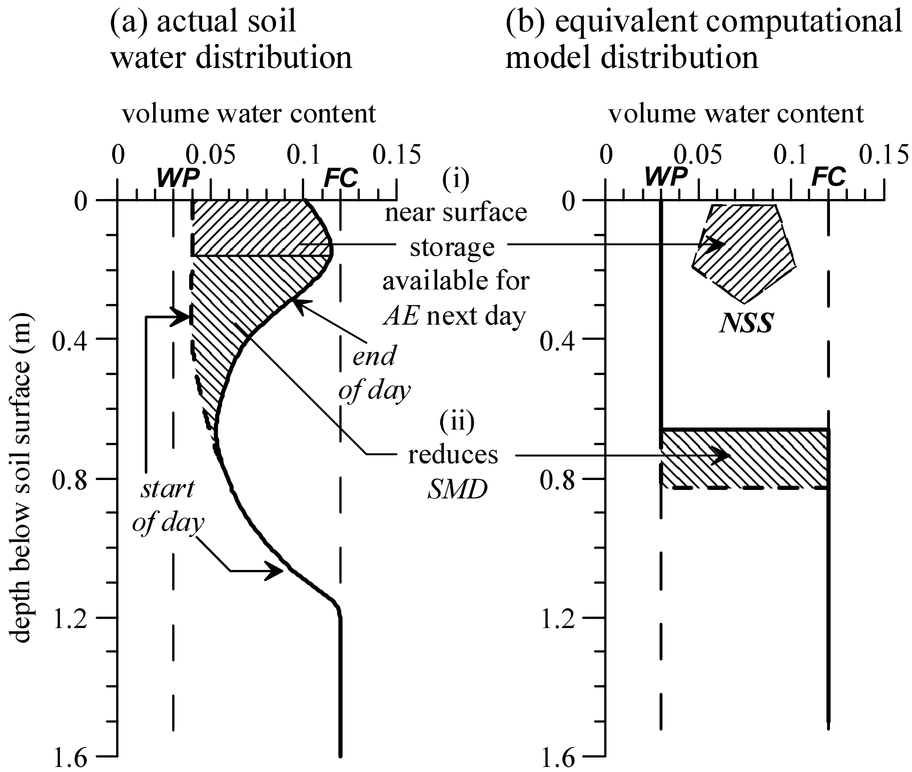
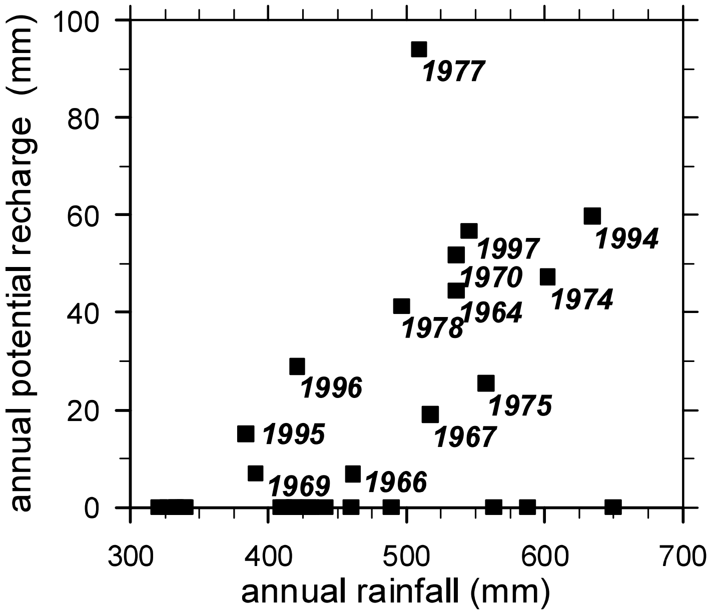
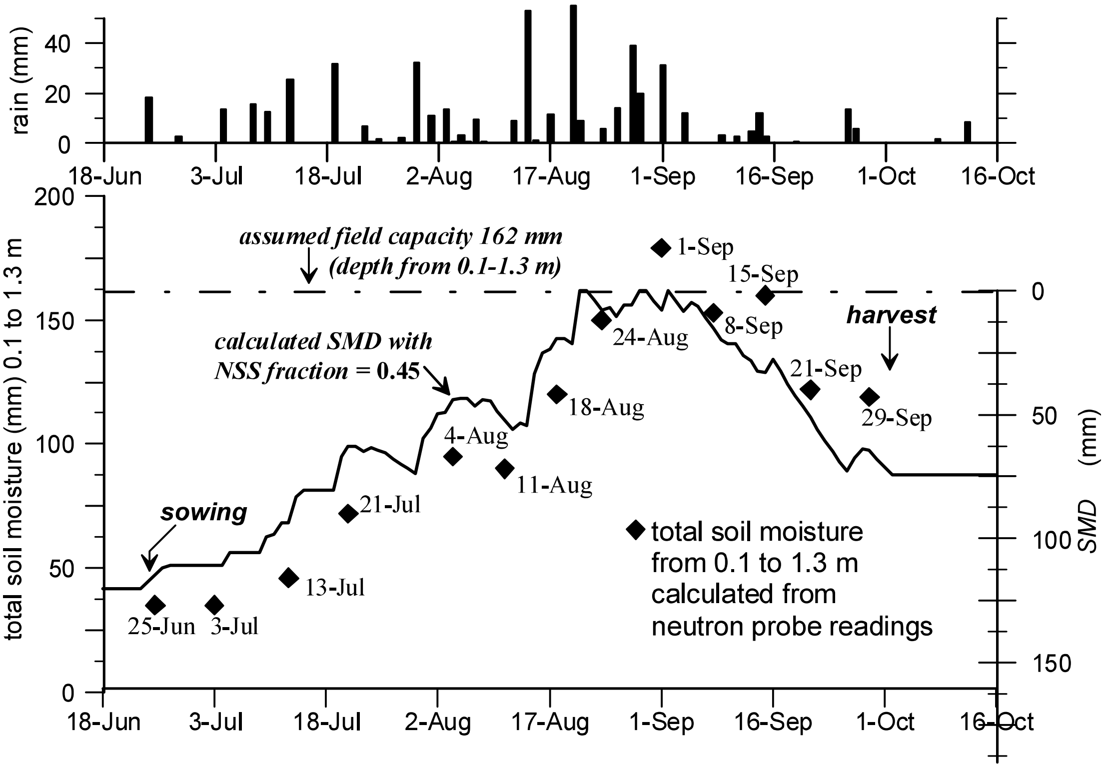

(a) actual soil water distribution
(b) equivalent computational model distribution
volume water content
0
0.05
0.1
0.15
WP
FC
(i) near surface storage available for AE next day
end of day
(ii) reduces SMD
start of day
NSS
depth below soil surface (m)
0
0.4
0.8
1.2
1.6

Figure 8



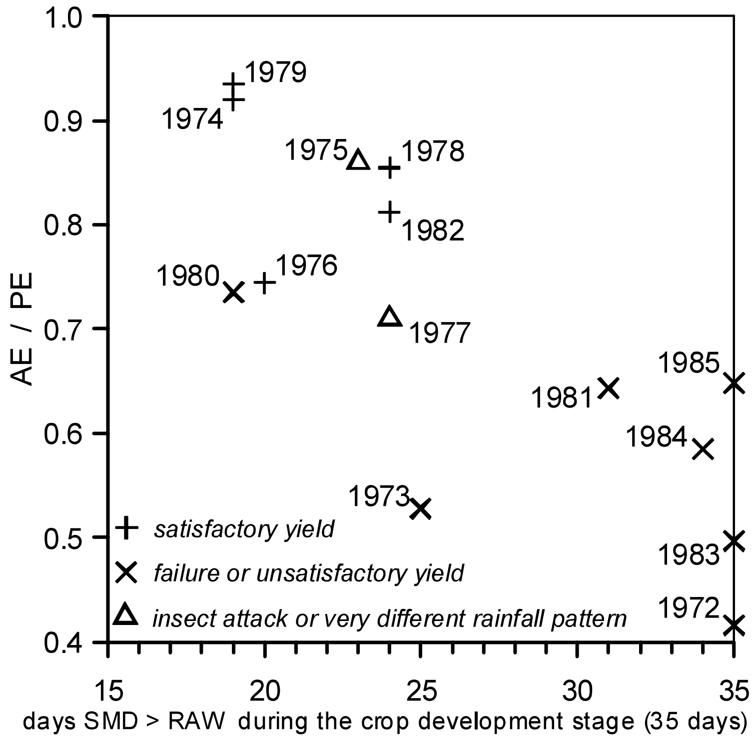
annual potential recharge (mm)
100
80
60
40
20
0
1977
1997
1994
1970
1974
1964
1978
1996
1975
1995
1967
1969
1966
300
400
500
600
700
annual rainfall (mm)

Figure 9



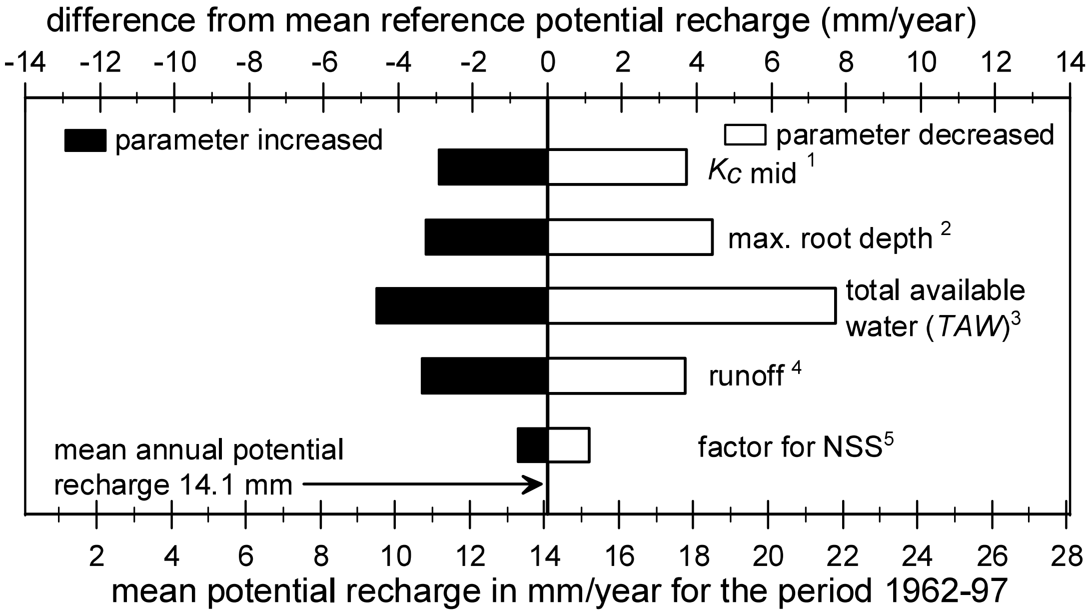
rain (mm)
40
20
0
18-Jun
3-Jul
18-Jul
2-Aug
17-Aug
1-Sep
16-Sep
1-Oct
16-Oct
200
150
100
50
0
total soil moisture (mm) 0.1 to 1.3 m
assumed field capacity 162 mm
(depth from 0.1-1.3 m)
calculated SMD with
NSS fraction = 0.45
sowing
harvest
25-Jun
3-Jul
13-Jul
21-Jul
4-Aug
11-Aug
18-Aug
24-Aug
1-Sep
8-Sep
15-Sep
21-Sep
29-Sep
total soil moisture
from 0.1 to 1.3 m
calculated from
neutron probe readings
SMD (mm)
0
50
100
150

Figure 10



1.0
0.9
0.8
0.7
0.6
0.5
0.4
AE / PE
15
20
25
30
35
days SMD > RAW during the crop development stage (35 days)
1979
1974
1975
1978
1982
1980
1976
1977
1981
1985
1984
1973
1983
1972
satisfactory yield
failure or unsatisfactory yield
insect attack or very different rainfall pattern

Figure 11



1. K_{C} mid (1.10 ± 0.10)

2. maximum root depth Z_r = 1.2 ± 0.25 m

3. available water *TAW* = 0.09 ± 0.02 $m^3.m^{-3}$

4. runoff coefficients ± 20%

5. factor for NSS, *FrNSS* = 0.45 ± 0.25

Table 1
Click here to download Table: Table-1.doc

TABLE 1 Inclusion of Near Surface Storage in daily soil water balance with units mm or mm/d; *FrNSS* = 0.45, *RAW* = 59 mm, *TAW* = 108 mm; tabulated values are rounded to one decimal place (*pSMD* and *pNSS* are values at the end of the previous day).

Day	*pSMD*	*In*	*In+pNSS*	*PE*	*AE*	*NSS*	to *SMD*
1	96.0	30.0	30.0	6.0	6.0	10.8	13.2
2	82.8	0.0	10.8	5.8	5.8	2.3	2.7
3	80.1	6.0	8.3	5.9	5.9	1.1	1.3
4	78.8	0.0	1.1	6.0	1.1 + 2.9*	0.0	0.0
5	75.9	0.0	0.0	5.8	3.8	0.0	0.0

*$AE = 1.1 + K_S \times 4.9$ where $K_S = (108 - 78.8)/(108 - 59) = 0.60$

TABLE 2 Runoff coefficients at specific rainfall intensities and soil moisture deficits

SMD at start of day (mm)	Rainfall intensity (mm/d)				
	0	20	40	60	80
0	0.10	0.15	0.30	0.45	0.70
20	0.07	0.10	0.25	0.40	0.60
50	0.00	0.05	0.20	0.35	0.55
100	0.00	0.02	0.10	0.20	0.40

Table 3
Click here to download Table: Table-3.doc

TABLE 3 List of model parameters, numerical values and sources of information for Nguru

Symbol	**Parameter**	**Value**	**Sources of information**
Pr	daily rainfall	variable	from meteorological station
ETo	reference crop evapotranspiration	variable	Penman-Monteith, Allen et al. (1998)
K_C	crop coefficient	1.1 (max)	Allen et al. (1998)
K_E	soil evaporation coefficient	1.05	Allen et al. (1998)
θ_{FC}	moisture content, field capacity	0.12 m^3/m^3	Grema and Hess (1994), Allen et al. (1998), Rockström et al. (1998)
θ_{WP}	moisture content, wilting point	0.03 m^3/m^3	Grema and Hess (1994), Allen et al. (1998), Rockström et al. (1998)
Z_r	depth of roots	1.2 m (max)	Allen et al. (1998)
Z_e	depth for drying by evaporation	0.25 m	Allen et al. (1998)
TAW	total available water	108 mm (max)	Equation (1)
TEW	total evaporable water	26 mm	Equation (2)
p	depletion factor	0.6	Rockström et al. (1998)
RAW	readily available water	65 mm (max	from TAW and p
REW	readily evaporable water	16 mm	from TEW and p
K_S	water stress coefficient	Fig. 6	Allen et al. (1998)
$FrNSS$	fraction for near surface storage	0.45	field evidence
RO	Runoff	Table 2	field evidence

Table 4

TABLE 4 Alternative methods of identifying the *onset of rains*

Author	Criteria for *onset of rains*
Benoit (1977)	Rainfall ≥ 0.5 *ETo* over any period followed by no more than 5 dry days
Kowal and Kassam (1978)	Rainfall ≥ 25 mm in 10 days with rainfall ≥ 0.5 *ETo* in next 10 days
Stern et al. (1982)	Rainfall ≥ 20 mm in 2 days with no dry spell exceeding 10 days during subsequent 30 days
Agnew (1991)	Rainfall ≥ 10 mm in 5 days with rainfall ≥ 10 mm in next 15 days
Sivakumar (1992)	Rainfall ≥ 20 mm in 3 days with no dry spell exceeding 7 days during subsequent 30 days