A simulation model to assess the effect of afforestation on ground-water resources in deep sandy soils+

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Abstract

The ACRU agrohydrological modelling system has been extended to simulate and assess impacts on water resources resulting from afforestation in deep sandy soils. A ground-water routine has been developed aimed at simulating the transpiration losses from soil-water extraction by deep roots, both within the intermediate soil zone and from the capillary fringe above the ground-water table. The subsequent influence on soil-water budgets, ground-water recharge, ground-water flux, water-table depletion and effective radius of the depression area are modelled on a daily basis. Verification studies show a very good fit between observed and simulated water-table fluctuations. Simulations of the effect of *Eucalyptus* plantations on the hydrological regime, which were performed for an area in Northern Zululand, are illustrated as an application of the model.

Introduction

The growth and survival of forests in marginal rainfall regions are influenced by the ability of the trees to extract soil water. Water supply for transpiration through the so-called intermediate zone below the conventional root zone and from the capillary fringe above the ground-water table can be a decisive factor in the water budget, particularly under forest plantations (Van Slycken and Vereecken, 1990). This supply of water is determined, *inter alia*, by the depth of the water table and the heterogeneity of texture and structure of the successively deposited soil layers.

The water-table depth is a function of the rate at which the vegetation is extracting water by the transpiration processes, the lateral ground water in- and outflows and of the rate at which the ground water is being recharged. Exotic timber plantations of, for example, *Eucalyptus* species and their clonal varieties, may disturb the natural water-table equilibrium as a result of their high transpirational demand throughout the year and their deep rooting system. Consequently, exotic timber plantations can lead to reduced streamflow and a local depletion of the ground-water table (Bosch and Hewlett, 1982). This is particularly applicable when the lateral ground-water inflow is slow and the utilised water cannot be replenished sufficiently by recharge. Similar to the cone of depression around an active well, a ground-water depression area may develop around a plantation (Rawlins and Kelbe, 1990). Water-table levels may be drawn down several metres due to afforestation (SRK Inc., 1985). This may result in the drying up of wetlands and streams close to the plantation. Wells could become dry because of the creation of such ground-water depression areas in their vicinity.

The ACRU agrohydrological modelling system serves as an existing infrastructure with which to simulate, *inter alia*, daily infiltration, evaporation, transpiration, land-use change effects and the soil-water budget (Schulze, 1989). A subroutine was developed to simulate water uptake by tap roots, capillary rise, ground-water recharge, ground-water fluxes and water-table fluctuation. A pilot study was undertaken, which was aimed at simulating and assessing the impacts on the water resources due to afforestation of *Eucalyptus* hybrids in deep sandy soils in Northern Zululand.

In this paper ACRU's ground-water submodel, its verification and an application south of Lake Sibaya in Northern Zululand are presented.

The ACRU agrohydrological modelling system

The core of the ACRU agrohydrological modelling system is a multi-purpose, multi-layer soil-water budgeting model based on physical conceptual principles and with a wide range of capabilities (Fig. 1). The model uses a daily time step and is structured to be sensitive to land cover and has been described in detail by Schulze (1989). The simulation of the water budget of the extended model is based on the principles described in the following sections.

Intermediate zone

Water which percolates through the lowest subsoil horizon, i.e. the B horizon, enters the so-called intermediate zone, which by definition is the zone between the B horizon and the top of the capillary fringe (Fig. 2). The soil physical parameters of the intermediate zone, i.e. its texture, porosity, field capacity and wilting point, have to be determined by laboratory investigations or estimated from field work or soil maps. The simulation of the soil-water content in the intermediate zone is based on average physical properties of the soil in that zone and is based on a cascading "tank"-type model.

Capillary fringe

The capillary fringe is located above the ground-water table. The height of the capillary fringe is a function of the soil texture. It is assumed as a working rule in this subroutine that the bottom 10% of the capillary fringe is saturated (thus, strictly speaking, belonging to the ground water). The water content of the remaining capillary fringe is in linear transition from a saturated soil moisture condition to the actual soil moisture content above the capillary fringe, which may be below FC (Fig. 2). This

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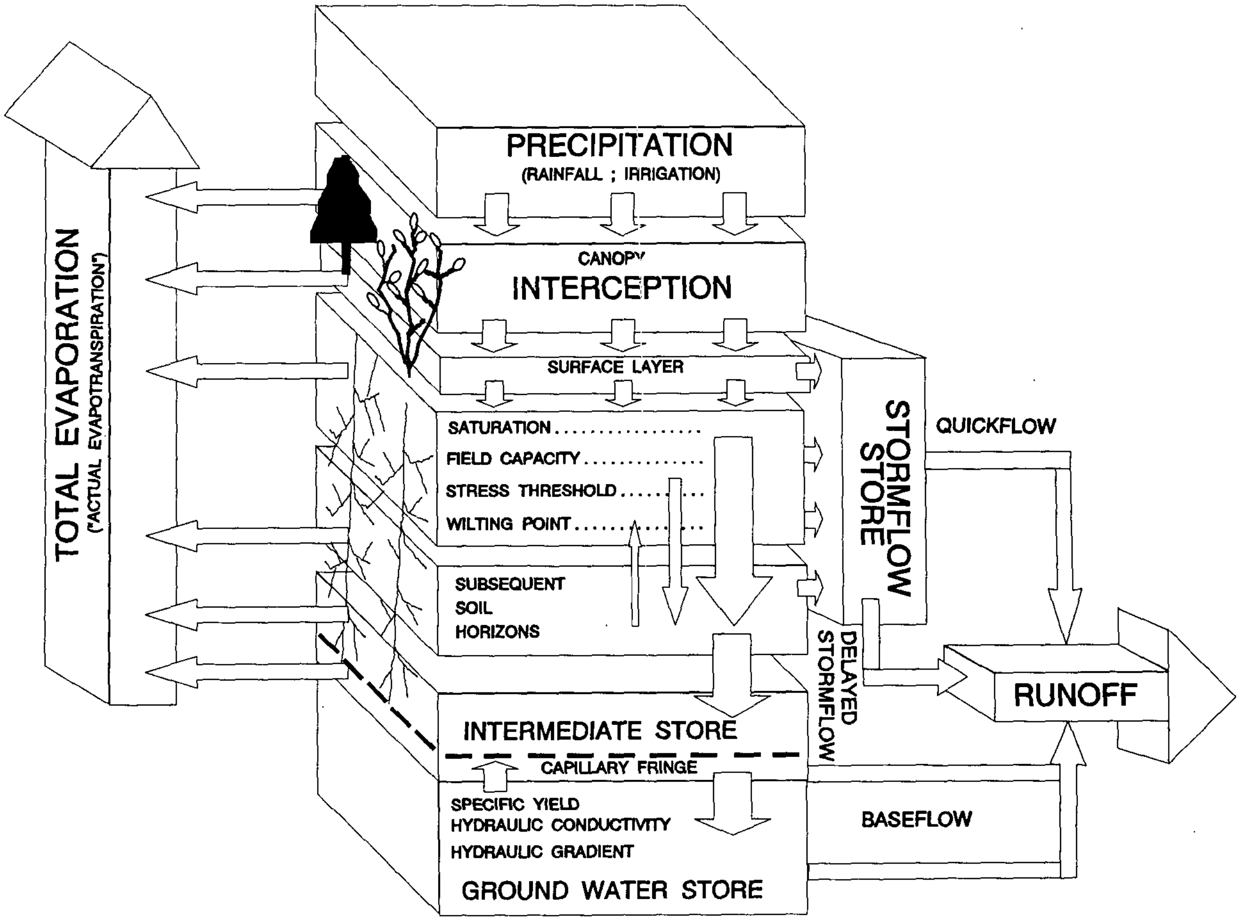

Figure 1
General structure of the extended ACRU modelling system

constitutes a simple but realistic model of the actual soil moisture distribution above the water table, because the matric suction above the water table will generally increase with height. Consequently, the number of water-filled pores will decrease in each soil as a function of the distance from the water table. When water is utilised within the capillary fringe by roots, this water moves upwards from the water table to the plant roots (case B in Fig. 2). The capillary yield is the quantity of capillary water in mm·d^{-1} for a given soil matric potential in the root zone, rising through a plane parallel to the phreatic surface and situated at a certain depth below the ground surface. Values for the capillary yield in mm·d^{-1} are predetermined in the model for 11 standard soil texture classes and 20 different distances between roots and water table (Arbeitsgruppe Bodenkunde, 1982).

Water-table rise

Any water percolating downward through the intermediate zone becomes part of the ground water. The water table rises according to the specific yield of the aquifer. The specific yield (S_y) of a rock or soil is the amount of water which after saturation, can be drained by gravity. Thus, it is the difference between porosity PO and field capacity FC (all elements in m·m^{-1}), *viz*:

$$S_y = PO - FC \qquad (1)$$

Lateral ground-water fluxes

The calculation of the lateral ground-water flux is based on the assumption of a homogeneous and unconfined aquifer. This assumption limits the application of the ACRU model to either very small areas or to regions which are known to be particularly homogeneous in terms of their geohydrological conditions. Following Darcy's law and the equation of continuity, DuPuit and Forchheimer developed an equation for ground-water flow in unconfined aquifers (Roudkivi and Callandar, 1976; Bear, 1979):

$$Q_g = \frac{(h_1^2 - h_2^2)\ K}{2L} \qquad (2)$$

where:

Q_g = ground-water flow in m^3·d^{-1} per m length of the receiving water body
h_1 = known pressure head at distance L from receiving water body (in m)
h_2 = pressure head of receiving water body (in m)
K = hydraulic conductivity of the soil (in m·d^{-1})
L = distance of h_1 from receiving water body (in m)

In ACRU, the calculation of inflowing ground water towards the simulation site from higher lying areas and outflowing ground water from the simulation site towards a receiving water body requires the variables and parameters as shown in Fig. 3.

In ACRU, $\mathbf{h_1}$ represents the height between the bottom of the flowing aquifer and the water table beneath the simulation site, $\mathbf{h_2}$ the height between the bottom of the flowing aquifer and the surface of the receiving water body and **L** the distance between the simulation site and the receiving water body. While l_a is the equivalent to **L** in DuPuit-Forchheimer's ground-water discharge equation, the factors h_1 and h_2 are calculated for every day of the

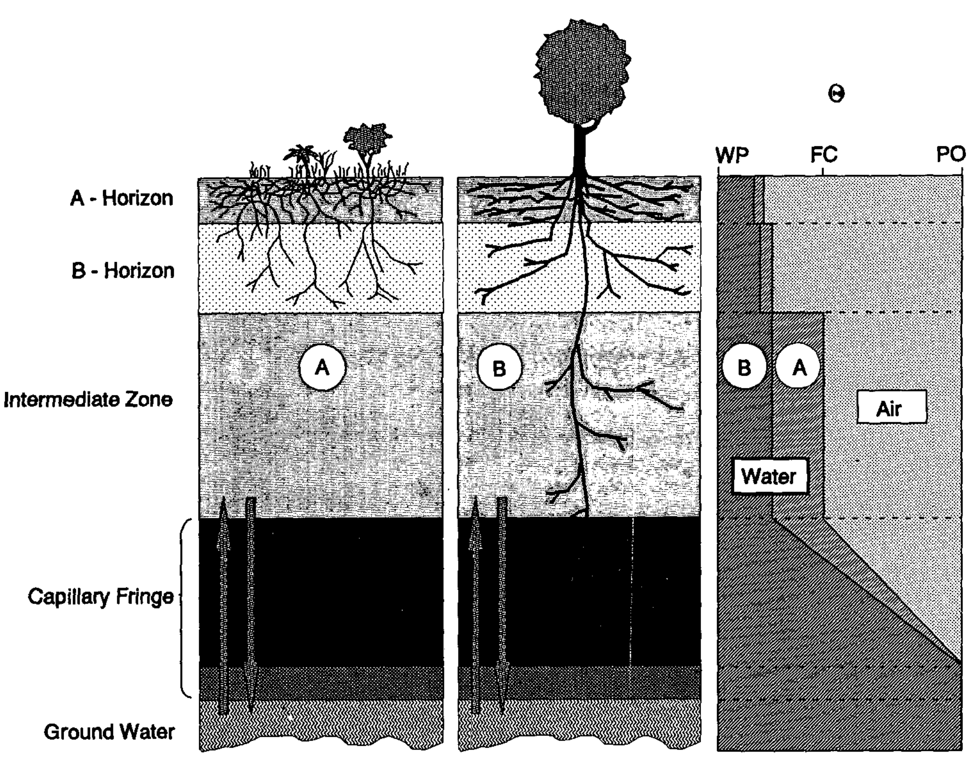

Figure 2
Schematic diagram of typical root and soil water distribution under (A) natural and (B) afforested conditions (Θ = water content, WP = wilting point, FC = filed capacity, PO = porosity)

simulation:

$$h_1 = d_{il} - d_{wt} \quad (3)$$
$$h_2 = d_{il} - (h_s - h_r) \quad (4)$$

Ground-water recharge and soil moisture content in the intermediate zone

The regulating factor of the recharge dynamics is the soil moisture content in the intermediate zone. Under shallow rooting vegetation the water content of the intermediate zone is considered to be always at field capacity, because:

- no water is consumed by plant roots within this zone; and
- water movement within sandy soils is negligible as long as the water is held by strong adhesive and capillary forces in the finer pores (situation A in Fig. 2).

As soon as water is consumed within the intermediate zone (case B in Fig. 2), the water content is decreased. Before ground-water recharge can take place in situation B, the intermediate zone first has to be filled entirely up to and beyond field capacity. When the intermediate zone is deep (in Northern Zululand between 3 and 10 m), only very high rainfall amounts would replenish the entire intermediate zone to and beyond field capacity.

It becomes apparent from Fig. 2 that in deep sandy soils the capillary fringe represents an important water source for deep rooting plants.

Plant physiological behaviour

The plant physiological behaviour, as simulated in the model, is

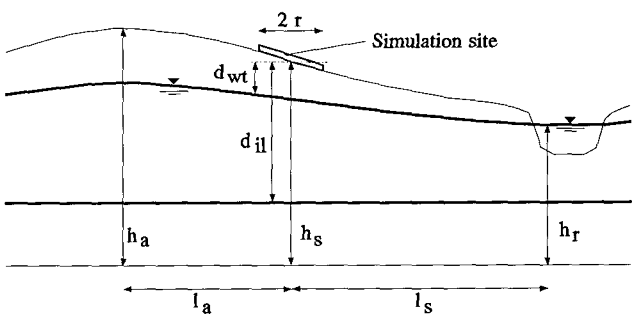

Figure 3
Variables and parameters required for ground-water flux simulation

l_s = *distance (in m) between the centre of the simulation site and the nearest receiving water body*
l_a = *distance (in m) between the centre of the simulation site and the highest elevation within the catchment under consideration*
h_s = *elevation (in m) of centre of the simulation site relative to mean sea level*
h_r = *elevation (in m) of the nearest receiving water body relative to mean sea level*
h_a = *elevation (in m) of the highest elevation within the catchment under consideration*
d_{il} = *depth of impermeable layer (in m) relative to centre of modelling site*
d_{wt} = *depth of water table (in mm) below the simulation site*

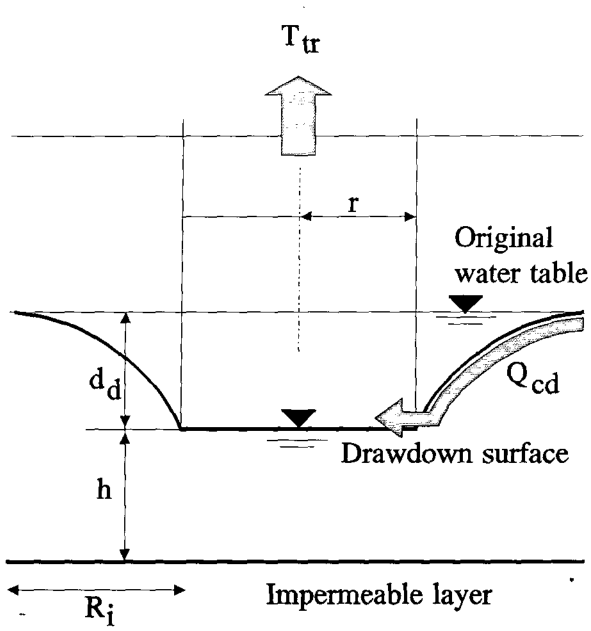

Figure 4
Variables and parameters required to simulate the ground-water flux towards the cone of depression

based on a number of assumptions. Deep roots include, in this routine, all roots that reach below the defined B horizon. They are "activated" when both A and B horizons cannot supply the transpirational demand of the plant. Even when tree roots completely colonise the soil, water uptake is restricted almost entirely to the upper soil horizons until the matric potential drops below a plant specific level (Waring and Schlesinger, 1985). Water is then extracted from progressively lower horizons, until the maximum rooting depth is reached. Based on this concept (case B in Fig. 3), the deep roots are assumed to extract water first from the intermediate zone (The estimation of the extent to which tap roots can extract water from the intermediate zone is difficult, because tap roots are not distributed evenly throughout the intermediate zone). Once the water content in the intermediate zone reaches a plant specific threshold value, additional water is extracted from the capillary fringe. When no more water can be extracted from the intermediate zone, all water required to maintain transpirational demand is drawn from the capillary fringe, provided it is accessible to the roots. Extraction from both the intermediate zone and the capillary fringe will result in a lowering or cessation of ground-water recharge, which, in turn, will cause a drawdown of the water table. It is assumed that the tap roots can follow the drawdown of the water table until they reach a plant specific maximum rooting depth. Haigh (1966), for example, excavated pine and eucalyptus roots under sandy conditions in Northern Zululand and found that taproots of mature *Pinus caribaea* reach deeper than 4 m, *P. elliottii* about 5 m and young *Eucalyptus* species below 2 m (where they reached the water table). However, much research is required to establish much needed knowledge on potential rooting depth of different species under a range of soil and climatic conditions. In any case, once the maximum rooting depth is reached, the distance between the active roots and the water table will increase steadily, until the hydraulic contact between roots and water table is interrupted. Under these circumstances, the plant can only extract water that is replenished from the surface as a result of either precipitation or irrigation.

Development and simulation of the depression area

In the same way that a cone of depression develops under an active well, a water-table depression area develops under any condition where water abstraction takes place. In order to simulate this depression area, knowledge on the reference water table or original piezometric surface is required (Fig. 4). This is the water-table depth that would develop if no depression area was present. The reference water table is simulated in ACRU by simulating the water-table depth under conditions without deep rooting plants. The ground-water drawdown is calculated by subtracting the simulated water-table depth under shallow root conditions from the simulated water-table depth under deep root conditions. Similar to the ground-water dynamics under an active well, the ground-water flow will react under conditions of deep rooting plants because of water utilisation from both the intermediate zone and the capillary fringe. The elements that determine the ground-water flux towards a depression area are explained in Fig. 4 and Eq. 5.

$$Q_{cd} = \frac{\pi \cdot K \cdot d_d^2}{\ln \frac{R_i + r}{r}} \qquad (5)$$

where:

- Q_{cd} = ground-water flow towards the depression area (in $m^3 \cdot d^{-1}$)
- K = hydraulic conductivity of aquifer (in $m \cdot d^{-1}$)
- d_d = depth of drawdown (in m)
- R_i = radius of influence (in m), i.e. the maximum distance to which the drawdown is effective
- r = radius of modelling site (in m)
- T_{tr} = transpiration of the plantation through taproots from both the intermediate zone and capillary fringe (in $mm \cdot d^{-1}$).

The variables d_d and R_i are calculated internally in ACRU, whereas r is calculated from the given size of the modelling site. The shape of the modelling site is idealised as a circle in order to facilitate the calculations.

Application of the model to simulate and assess the impact of afforestation on ground-water resources

The most important input variables into the ACRU modelling system include daily rainfall, daily potential evaporation, monthly land-cover information such as leaf area index, crop coefficients, root distribution and interception, soil physical variables such as texture class, porosity, field capacity, wilting point, depth of A and B horizons and geohydrological data, including specific retention, specific yield, hydraulic conductivity, gradient of the water table and initial water-table depth. The model simulates, on a daily basis, *inter alia*:

- effective rainfall (rainfall minus storm flow, minus interception) (Under conditions of sandy soils as found in Northern Zululand, storm flow occurs very seldom, when rain intensity exceeds infiltration capacity of the soil);

- total evaporation (transpiration from A and B horizons, from the intermediate zone and from the capillary fringe plus evaporation from the soil surface);
- the soil-water budgets for A and B horizons and the intermediate zone;
- ground-water recharge;
- drawdown of the water table;
- ground-water fluxes;
- depth of the depression area; and
- effective distance of ground-water drawdown.

In order to assess the effect of afforestation on ground-water resources, the water resources under afforested conditions of a selected area are compared to those under natural vegetation conditions of that area. First, a base simulation was performed in order to ascertain the present state water regime conditions and to verify the model. Simulations of ground-water levels in several areas of the coastal zone of Northern Zululand in Northern Natal, north of Sordwana Bay and south of Lake Sibaya, were performed (Fig. 5). The climatic "driver" station MBAZWANA (Weather Bureau number 0412180) for modelling purposes is situated in the centre of the study area at 27°29' S, 32°36' E and has a record length of 34 years of reliable daily rainfall data.

The typical soil of the study area is a medium sand (Fernwood) with a clay fraction below 6%. This soil is characterised by a very high final infiltration rate of approximately 360 mm·h^{-1} (Kruger, 1986), a porosity of 0,4 m·m^{-1} by volume and a field capacity of 0,1 m·m^{-1}. With a wilting point at 0,035 m·m^{-1}, this leaves only 0,065 m·m^{-1} by volume for plant available water. The low field capacity indicates that only small amounts of water can be held against gravity and that these soils allow frequent ground-water recharge to take place, as long as the water held in the subsoil is not utilised by deep rooting plants.

Estimations of geohydrological model input were based on information from adjacent and similar areas and the experience of those field workers who had previously undertaken geological research in the study area (Tinley, 1976; Kruger, 1986; Martinelli and Associates, 1987; Meyer, 1991). No additional field tests were conducted for this study. The only recorded ground-water level information available for the study area is on a few wells which have a limited record of ground-water level data.

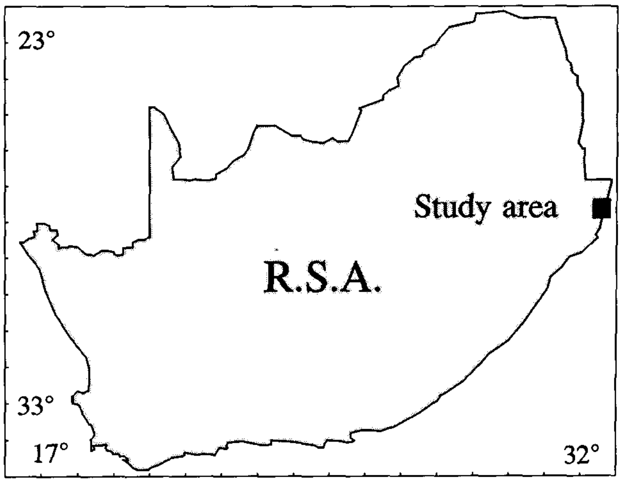

Figure 5
Location of study area

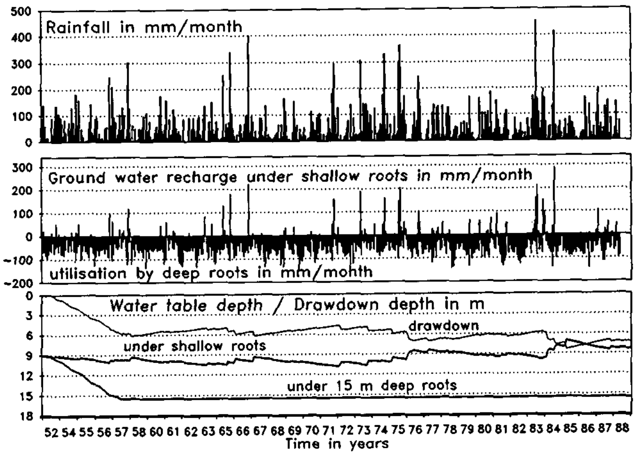

Figure 6
A 34-year simulation of the replacement of 100 ha of shallow rooting natural vegetation in Northern Zululand with deep rooting Eucalyptus grandis

Hydrological assessment of the present land-cover situation

Areal proportions of the most important vegetation types were obtained for each of the modelling sites. Monthly values for interception loss, crop coefficient, root distribution and rooting depth were derived and estimated for all vegetation types present as input into the hydrological model. Estimations on the typical water-table depth within modelling sites were made, based on field observations and experience by Meyer (1991) and others, and incorporated into the model. Because the water-table depth is a function of the recharge rate (relatively easy to determine) and baseflow (relatively difficult to determine), the following approach was used in order to test the geohydrological parameters.

The ACRU model was run to simulate 34 years (1952 to 1988, with three years being discarded because of insufficient daily rainfall data), using daily rainfall data as the determining changing parameter. The period of record under consideration from 1952 to 1988 includes dry and wet periods and shows a slightly positive overall rainfall trend (a result of the cyclones Domoina and Imboa in 1984). A fluctuation of the water table around a mean water-table depth with a similar trend can be expected. The fluctuation is the result of higher recharge during relatively wet years and lower or zero recharge during relatively dry years. The latter results in a depletion of the ground-water table in these years. Because no significant land-cover changes during the test period are assumed and no climate trends are evident, a fluctuating and overall slightly rising water table is to be expected. A model output, resulting in a trend in either depletion or a rise of the water table, would have indicated that the geohydrological parameters were chosen incorrectly and needed correction.

Only when the model output showed an oscillation around a stable water-table depth, a realistic equilibrium between recharge rate and baseflow was ensured (Fig. 6). This condition was achieved with ACRU without parameter calibration and on the first run.

Concepts governing water-table fluctuation

The following concepts governing water-table fluctuation are incorporated into the model and are represented in Figs. 2 and 6, *viz*:

- Ground-water recharge can only take place after:
  - high rainfall events that result in infiltration and the sequential filling of the stores of the A and B horizons as well as the intermediate zone above field capacity; and
  - lower rainfall events that fall on a catchment where antecedent moisture conditions facilitate the downward water movement.
- Ground-water recharge results in a rising of the water table and the associated capillary fringe (indicated by upward arrows in Fig. 2).
- During times of no ground-water recharge, lateral ground-water flux results in a falling of the water table (downward arrows in Fig. 2). The lateral flux and subsequent depletion is governed by the hydraulic gradient. The higher the water table, the faster flux and depletion occur. Consequently, in a period of no recharge, water-table level depletion decreases exponentially.
- Under a vegetation cover with deep roots recharge takes place more seldom or even not at all because the intermediate zone is utilised to such an extent that its soil moisture content never reaches field capacity. The prevention of recharge and additional utilisation of water from the capillary fringe result in a depletion of the water table. The dryer the overall climatic conditions, the more water is utilised from the intermediate zone and the capillary fringe. This is indicated clearly in drought periods, e.g. 1961/62 or 1982 (Fig. 6).
- The ground-water flux towards the depression area is governed by the depth of the drawdown.
- The combination of recharge and depletion results in the fluctuation of the water table as is shown in Fig. 6.

Verification study

After the ACRU model had been run, results of the fluctuating water-table depth were compared with data from three boreholes within the study area, where monthly water-table data are available. Borehole data obtained from Martinelli and Associates (1987) and from Mondi Forests (Kewley, 1991) were compared with results obtained by modelling the present vegetation conditions. Figure 7 presents a comparison of measured borehole data and simulated water-table depth for one of the simulations.

Verification results reveal that estimations of water-table depth are very good in two cases and slightly underestimated in one case. In all cases the amplitude of oscillation appears to be slightly underestimated by the model. This could be an indication of an underestimation of either the hydraulic conductivity or the hydraulic gradient of the ground-water flow. Furthermore, Meyer (1989) reports recharge rates in the study area around Lake Sibaya of 21% of the mean annual precipitation (MAP). An average recharge value of 20,2% of MAP was calculated by ACRU for the study area - an excellent comparison with Meyer's value.

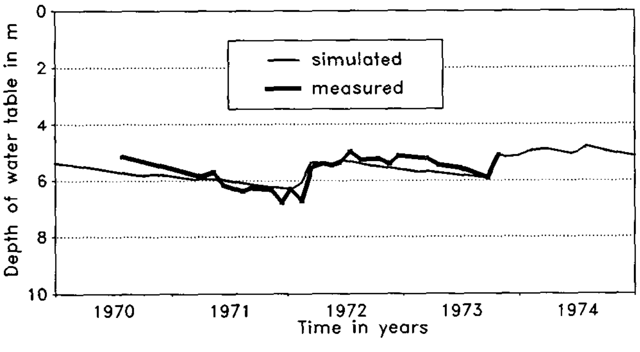

Figure 7
Comparison of measured versus simulated water-table fluctuation at a borehole 6 km south of Lake Sibaya

Simulating the impact of afforestation on ground-water resources

After the model had been run for typical natural conditions, it was rerun with the natural vegetation input variables replaced by those for *Eucalyptus* species. Hydrologically, a *Eucalyptus* plantation differs markedly from natural vegetation. In order to simulate the effect of a *Eucalyptus* plantation on the water budget, model input parameters such as interception losses, leaf area index, crop coefficients, soil-water extraction patterns and root distribution in the A and B horizons as well as maximum depth of the tap roots were changed. The maximum rooting depth of *Eucalyptus* species under the physiographic condition found in the study area is not known. For South Africa, rooting depth of *Eucalyptus* plantations is known to reach 8 m and probably much deeper (Haigh, 1966; Dye, 1991). In Australia rooting depth for *Eucalyptus* species has been reported to reach 18 m (Carbon et al., 1980) and 28 m (Nulsen et al., 1986) in a jarrah forest environment. An Australian study has shown that the density of fine roots does not decrease significantly between approximately 4 and 15 m (Carbon et al., 1980). This enables the trees to extract water in the intermediate zone at a rate that enables the tree to transpire at relatively high rates, even when the topsoil horizons are completely dry.

Because of the uncertainty of the maximum rooting depth the model was applied three times at each of the nine sections, assuming maximum rooting depths of 10, 15 and 20 m respectively.

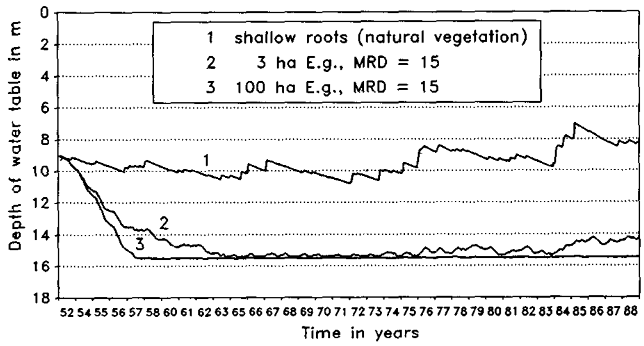

Figure 8
Time series of typical water-table fluctuation of plantations of different areal extent in Northern Zululand (E.g. = Eucalyptus grandis, *MRD = maximum rooting depth in m)*

Results of the simulation

An example of the water-table depth time series is given in Fig. 8. In the area beneath mature *Eucalyptus* plantations the natural recharge rate was simulated to be zero, because:

- the trees intercept a larger amount of daily rain than natural veld (minor factor); and
- the depleted intermediate zone was simulated not to reach field capacity due to previous regular root abstractions out of this zone.

Reduced recharge rates and water abstractions from the capillary fringe under *Eucalyptus* forest result in a ground-water drawdown, which must be understood as an artificially induced lowering of the water table. The deeper the tap roots (Fig. 9) and the larger the area of a plantation (Fig. 8), the deeper the drawdown will be. For example, an area covering 3 ha of *Eucalyptus* species with an assumed rooting depth of 15 m would cause smaller drawdown than a plantation of the same species covering 100 ha (Fig. 8). This can be explained by the relatively smaller contribution of the ground-water flux towards the depression area under a larger area in terms of area weighted flow depth (flow divided by area).

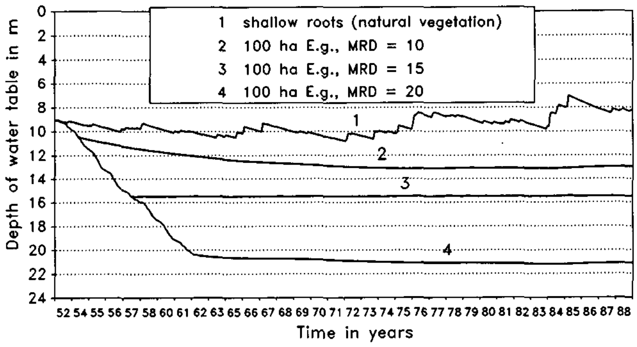

Figure 9
Time series of typical water-table fluctuation of Eucalyptus grandis *(E.g.) plantations, with different assumed maximum rooting depths, in Northern Zululand (MRD) = maximum rooting depth in m)*

Figure 9 presents water-table depletions under a 100 ha large area with *Eucalyptus* forest. Because no recharge is simulated to take place under an established *Eucalyptus* plantation, the drawdown is a function of the maximum rooting depth and the existence of water bodies in the vicinity of the plantation. Assuming a maximum rooting depth of 10 m in Fig. 9, a fast drawdown during the first two years would occur due to the elimination of ground-water recharge and the tapping of the capillary fringe. As soon as the tap roots cease to tap the capillary fringe, the drawdown then remains only a function of lateral ground-water flow and the flow towards the depression area. This is indicated by a slower overall lowering of the water table. In this simulation, the nearest water body has an elevation of typically 15 m below the site of the plantation.

If a maximum rooting depth of 15 or 20 m is assumed, the tap roots will cause a deeper drawdown as a result of ongoing water abstraction from the capillary fringe. The balance of inflowing water and utilised water is governed by the atmospheric demand, the soil moisture status of the upper soil layers and the depth of the drawdown.

Typical drawdown values for the nine modelling sections in the study area, assuming 100% *Eucalyptus* plantation and a maximum rooting depth of 10, 15 and 20 m, are 4, 6 and 12 m respectively.

Results and performance of the model are, in terms of soil moisture movement, ground-water recharge and water-table movement, in keeping with results from studies undertaken elsewhere in South Africa (Lindley and Scott, 1987; Rawlins and Kelbe, 1990; Dye and Poulter, 1990) and in other parts of the world (Allison and Hughes, 1972; Carbon et al., 1982; Greenwood et al., 1982; Bren and Turner, 1985; Talsma and Gardner, 1986; Bell et al., 1990).

Conclusions

The ACRU modelling system has been extended to enable simulation of impacts of afforestation on ground-water resources. Under conditions of a homogeneous and unconfined aquifer, ACRU is able to simulate:

- the soil-water budget in the intermediate zone;
- water extraction from the capillary fringe due to tap roots;
- ground-water recharge;
- water-table fluctuation;
- drawdown of the water table; and
- the effective radius of the depression area.

The simulation of water-table fluctuation, in the deep sandy soils of Northern Zululand, shows agreeable comparisons with observed borehole data.

Results of a simulation with *Eucalyptus* species indicate a significant change in the ground-water recharge regime. Decreased recharge rates and additional water abstractions of tap roots within the capillary fringe result in a drawdown of the water table of several metres within a few years. The speed and extent of the drawdown is governed by the extent of the plantation and the maximum rooting depth of the tree under consideration. In an application in Northern Zululand, the drawdown is simulated to vary from a few metres to as much as 12 m in the worst case scenario.

Further verification over a wider range of conditions will test the performance of the model and enable its final validation. The performance of the ACRU modelling system is encouraging and results obtained are expected to be of high value for planners and decision-makers both in the environmental field and the forestry industry.

Acknowledgements

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