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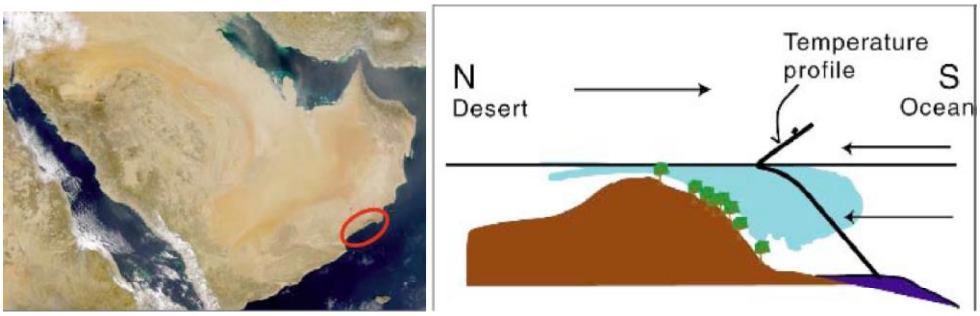
IMPACT OF THE DHOFAR CLOUD FOREST ON SUBSURFACE HYDROLOGICAL FLUXES: MODELLING ON THE SCALE OF A NEAR-ROOT ZONE SOIL CONTINUUM

A slope forest in a semi-arid region of Oman is studied. The peculiarity of this ecosystem is an interception of the liquid (fog and drizzle) by the tree canopy from a monsoon wind during a three-month monsoon period. The intercepted water drips on the soil from the foliage and stem over the area of the projection of the canopy. The moisture accumulates in the soil profile and is used by the tree long after the monsoon. Capillarity and gravity drives moisture to the water table. A modified Green-Ampt model of vertical infiltration is suggested, with a cyclostationary «self-drip-irrigation», vertically non-uniform water uptake by the tree roots and the possibility of stopping of the fronts of a descending water slug owing to non-equal capillary pressures on the imbibition and drainage fronts of the slug.

Key words: *deciduous cloud forest, arid/semi-arid region, hillslope vegetation, orographic rain, root water uptake, infiltration, Darcy law, Green-Ampt model.*

Introduction. In arid and semi-arid climates, which we, following [1], call water-limited environments (WLE), the soil moisture, salinity and temperature stresses determine the performance of plants. In these environments emerge interesting patterns of soil water, which are associated with the spatial distribution of vegetation [2]. In comparison with crops, pastures, grasslands or shrublands, forests are usually considered more water demanding [3]. In WLE higher water consumption of trees or shrubs is often explained by the ability of deep rooted vegetation (such as perennial trees or shrubs) to access water from a deep wet soil and even directly from the water table [4] (other plants with lower water use and with shallower roots



a) *b)*

Fig. 1. Satellite image of the study area (a) and vertical section of the mountain ridge, forest, monsoon and temperature profile (b)

can not do this). As a result of a combined water uptake by the roots from the soil, deep vadose zone and aquifer, the experimental data [1] in Kalahari showed that on the scale of 0-60 m from the top soil to the water table the moisture content decreases in the first few meters, then remains almost constant (for approximately 5–25 m from the surface) and then increases again (25–60 m) close to the capillary fringe, with a full saturation on the phreatic surface. This «trough»-shaped moisture profile is attributed to the vertical water-hunting activity of deep tree roots.

In this paper we consider infiltration (and water uptake) of a semi arid forests in South-West Oman, in the governorate of Dhofar (in Fig.1, *a* a wite oval illustrates the study area on the the Arabian peninsula). The Dhofar cloud forests are extraordinary eco-hydrological systems, since their existence depends on their ability to self irrigate their root zone through interception of cloud water by the tree crowns [5, 6]. A vertical cross-section of the forest belt is shown in Fig.1b. The forests thrive in a seasonal climate with a 3 months humid (and foggy) season, which lasts from mid June to mid September, followed by a 9 months dry season. The characteristic monsoon fog is caused by orographic clouds, which are formed when moist air from the sea is pushed up against the coastal mountain range from South to North. The annual precipitation in this area is 250 mm, most of which falls during the monsoon in the form of light drizzle (on the average 2mm /day). The other major source of rainfall is cyclones, which – due to high intensity and prevailing runoff – seem, however, not to penetrate the deep soils as thoroughly as the precipitation during the monsoon [7] concluded that water, received below the tree crowns, consists of about one third of rainfall and two thirds of intercepted cloud water. This leads to a pattern where more soil water infiltrates below the tree crowns as compared to a bare soil.

A typical desiduous tree is shown in Fig. 2. Trees of this type may form a cluster with overlapping canopies.

Fig. 2. A typical tree of the cloud forest in the study area

It is noteworthy that the tree-induced drip self-irrigation in Dhofar forests guided the local engineers to install a net-mesh devises mimicking the canopy as fog-drizzle collectors with up to 58 liters/day/m^2 of the mesh water condensate productivity (see, e.g., [8]).

Cloud interception is reported from many cloud forests (i.e. [9, 10]), but particularly in semiarid cloud forests, the additional water may substantially contribute to maintaining lush vegetation in a comparatively dry environment [11–14, 6]. To the best of our knowledge, in earlier works on fog forests (both humid and semi-arid) the dynamics of dripped/infiltrated water in the soil and vadose zone has not been studied in detail and only occasional measurements/modeling of the soil moisture (or capillary pressure), evaporation rate from the soil surface and soil temperature were reported. This is understandable because collecting field data from the whole soil- vadose zone – capillary fringe profile in the vicinity of a tree is instrumentally cumbersome. Indeed, belowground hydrological sensing, e.g. with TDR, C- or Theta-probes would require a good vertical density of instruments in a borehole. Even piezometers (deep in WLE) should be close to the tree trunk and well adjusted to intermittent recharge pulses from the vadose zone subjacent to the tree, with a good separation of the superjacent tree-generated recharge pulses from regional groundwater flow fluctuations or cyclicity. So, the objective of this paper is to develop a simple mathematical model, applicable to field conditions (i.e. having as few parameters as possible), that would predict the following fog-forest specific infiltration scenarios: depth-time- varying input from the soil surface, depth-timevarying water uptake by the tree roots, and ascending direction of the travel of the moisture content maximum as in [15]. The model should predict how the water content varies with time and depth, in particular, the «trough» –type moisture profile of [1].

Physical and Mathematical Model. We consider a tree of a fog-forest and neglect the interference of the drip zones of neighbouring trees (Fig. 3). Alternatively, Fig. 3, *a* can be viewed as a tree cluster with an «effective canopy» (and «effective» infiltration). The real dripping intensity, i_d, radially decreases from the axis of the infiltration zone (stem flow «funnel») to the periphery of the canopy projection on the ground surface. Outside the throughfall zone (of radius R and area A) the intensity of background precipitation, i_b, does not vary with the radial coordinate r counted from the stem axis. Both i_d and i_b depend on time. The dependence i_d (r) is seldom measured and we assume in the model that $i=I_d(t)$ is an average value for both the stemflow and throughfall integrated over r.

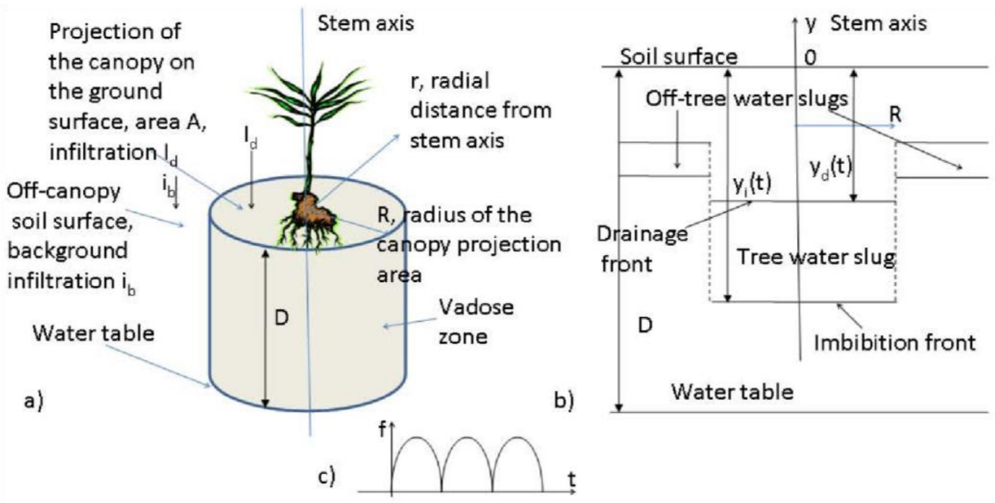


Fig.3. 3-D schematization of tree and subjacent soil (a), axial cross-section of the subsurface with water fronts (b), cyclostationary component of water uptake function by roots (c)

We assume the following: For one monsoon period I_d continues from t=0 till t=T=const. Outside this time interval I_d=0. The intensity of infiltration during $0<t<T$ is high enough so

the soil surface is completely saturated. At t=0 a saturation (imbibition) front $y_i(0)$ appears and propagates downward as $y_i(t)$ with a vertical axis of a Cartesian coordinate system oriented upward. A purely vertical infiltration takes place and we adapt the Green and Ampt (GA) model [16] both in the under-canopy zone and outside this zone. Without any loss of generality, we suppose that during the monsoon period, transpiration is relatively small and the water uptake from the saturated zone is negligible (corresponding to [7]). Then for assumed 1-D infiltration the position of the front over the interval $0<t<T$ in both zones is described by the well known analytical solution of Polubarinova-Kochina [17]. The focus of our modelling exercise is in what happens after t=T, i.e. after the end of the monsoon, when infiltration ceases and transpiration starts.

When t>T another upper desaturation (drainage) front, $y_d(t)$, $y_d(0)=0$ is formed. Obviously, $y_d(t)<y_i(t)$ and this inequality should hold for any time. The four fronts are shown in Fig. 3, *b* (vertical axial cross-section of Fig. 3, *a*) and we neglect the smearing effect on the cylindrical surface separating the zones of contrasting infiltration rate (dashed lines in the Fig. 3, *b*). For the sake of brevity we will study two under-tree fronts only. We track y_i until the instance T_a when this advancing front arrives at the water table (depth D). After that time a groundwater mound is formed [17] and the GA model does not work.

We assume that the porous medium is homogeneous, isotropic and incompressible, water is incompressible and flow obeys the Darcy law. We introduce the pressure head p=h-y where h(y,t) is the hydraulic head within the water slug located in between the two fronts, $y_i(t) <y< y_d(t)$. The basic assumptions of the GA model are: a) in the slug water is under tension but completely saturates the pore space, b)the hydraulic conductivity in the slug is k=const that coincides with the saturated conductivity, c) water moves in the slug only, i.e., ahead of the advancing front and behind the retreating front k=0.

The GA model postulates that on the front $p=-p_c$ =const. This front pressure head is one of two physical parameters of the model (another is k). Both p_c and k are tabulated for common porous materials (see, e.g. [17]). In our case of a two-front slug in Fig. 1 we assume

$$p=-p_i, \text{ at } y=y_i, \; p=-p_d \text{ at } y=y_d, \tag{1}$$

where p_d and p_i are two given positive constants. Commonly, $p_d > p_i$ that on the meniscus level of an individual soil pore corresponds to a higher contact angle of the advancing front compared to the retreating one. In our model, however, the inequality can mathematically have an opposite sign.

From the Darcy law the specific discharge q(y, t) is:

$$q = -k\frac{dh}{dy}. \tag{2}$$

We assume that water is lost from the moving phase of the slug to an immobile (with respect to the soil) storage, which is prevalently due to the uptake by the roots but can also involve sorption into a stagnant film around once wetted soil particles (or water interception in dead-end pores). The intensity of this «sink» tapping the Darcian water is E(y, t). From conservation of mass the total vertical discharge through any vertical cross-section of the cylinder in Fig.1, *a* is Q=A q and we have

$$\frac{dQ}{dy} = E(t, y). \tag{3}$$

Thus E in (3) is the intensity of interception of vertical descending seepage into an immobile liquid (root) compartment. Within the roots the moisture keeps moving (upward, laterally or downward, see [1] but this in-root motion does not affect the GA motion in the soil. A similar model with a distributed sink term is used in the Dupuit-Forchheimer approximation of prevalently horizontal groundwater flow in an unconfined aquifer [17]. In our case E also should be small enough for the basic model assumption of vertical infiltration to hold. Integration of (3) yields:

$$\int_{-D}^{0} E(t,y)dy = Q_s(t),$$

where Q_s is the total liquid flow rate, diverted from seepage to roots. We will assume that all Q_s are converted into the sap flow, i.e. thus ignoring tree root internal storage and evaporation from the upper front. Moreover, this assumption ignores a potentially complex topology of water motion within the root system [1], which one can hardly measure.

Combining (2) and (3) we get the governing equation

$$\frac{d^2h}{dy^2} = -e(t,y), \tag{4}$$

where e=E/(A k). This equation is similar to one for the water table dynamics in an unconfined aquifer with a spatially nonuniform and transient recharge [17]. We assume

$$e(t,y) = e_0 f(t) \exp[\alpha y], \tag{5}$$

where α is a constant, characterizing the root system, and f(t) is a function, characterizing a season-dependent uptake of the whole root continuum (one example of this function is shown in Fig. 3, *c*). Instead of an exponential decrease of the uptake with depth, in (5) any other function can be taken (see, e.g. [18]). If f=const and α=0 then the water uptake is steady and uniform within the travelling slug. We recall that the GA limitations require that neither capillarity nor uptake create unsaturated conditions in the slug.

Integration of (4) gives:

$$h(t,y) = c_1(t) + c_2(t)y - e_0 f(t) \exp[\alpha y]/\alpha^2, \tag{6}$$

where c_1 and c_2 are two functions which are expressed from the boundary conditions (1) applied on both fronts:

$$\begin{aligned} h(t,-y_i(t)) &= c_1(t) - c_2(t)y_i(t) - e_0 f(t)\exp[-\alpha y_i(t)]/\alpha^2 = -y_i(t) - p_i \\ h(t,-y_d(t)) &= c_1(t) - c_2(t)y_d(t) - e_0 f(t)\exp[-\alpha y_d(t)]/\alpha^2 = -y_d(t) - p_d. \end{aligned} \tag{7}$$

Eqns (7) make a system of two linear equations with respect to c_1 and c_2 from which we immediately obtain by eliminating c_2 the following expression:

$$c_2(t) = 1 + \frac{p_i - p_d}{y_i - y_d} - \frac{e_0 f(t)(\exp[-\alpha y_i] - \exp[-\alpha y_d])}{\alpha^2 (y_i - y_d)}. \tag{8}$$

The expression for c_1 and elimination of this function follows from the first equation in (7).

On the fronts the linear average velocity and Darcian velocity are related through the so-called kinematic boundary conditions [17]:

$$\begin{aligned} m_i \frac{dy_i(t)}{dt} &= k\frac{dh(t,-y_i(t))}{dy} = k[c_2 - e_o f(t)\exp[-\alpha y_i(t)]/\alpha] \\ m_d \frac{dy_d(t)}{dt} &= k\frac{dh(t,-y_d(t))}{dy} = k[c_2 - e_o f(t)\exp[-\alpha y_d(t)]/\alpha], \end{aligned} \tag{9}$$

where m_d and m_i are constant effective porosities on the corresponding fronts. Normally $m_d < m_i$ (if the slug propagates through a dry soil) but mathematically the sign of this inequality can be opposite. Eqns. (9) constitute a system of two ordinary nonlinear differential equations [19] with respect to $y_i(t)$ and $y_d(t)$, c_1 and c_2 taken from eqns (7)–(8). Without any loss of generality we rescale time as t_r=t-T and drop «r» as a subscript. Then the initial conditions for eqn. (9) are:

$$y_d(0) = 0, y_i(0) = 0, \qquad (10)$$

where y_0 is a given monsoon-wetting depth, which we retrieve from the monsoon stage of infiltration.

If both fronts asymptotically (effectively) stop before reaching the depth D then the slug «hangs» in the vadose zone, waiting for the next-season stronger slug to come, overtake the stopped one and resume the descending motion as a «merged» slug. If f(t) is high enough then the drainage front eventually catches the imbibition one. Mathematically, the Cauchy problem can be solved for any $|y_i(t)|<|y_d(t)|$ but physically this inequality is unrealistic. If it appears from integration of (9)–(10) this means that the GA model becomes inapplicable, i.e. a tension-saturated flow can not be realized. Then an unsaturated flow model should be used as in e.g. [15].

Modeling Results. For a free standing tree 3 m of the canopy projection radius is a large crown. In Gogub site of Dhofar the average distance between trunks is 2.5m. The trees there are arranged in clusters, one cluster containing five and more stems in a very small area (1 m radius). The average distance between the clusters is much larger (about 5 m). In computations below we selected 1.5 m as the crown radius i.e. a tree density of 0.14.

Soil properties under the trees varied and systematic hydropedological studies were not undertaken in the study area. For the modeling below we assumed that the soil is a laveen loam (43% sand, 44% silt, 13% clay according to the USDA taxonomy [20]). From experiments in [20] k=0.216 m/day, p_d=0.47 m, p_i=0.22 m. Without any loss of generality we assumed D=20 m, m_d=0.2, m_i=0.3. The annual rainfall outside the canopy is about 100 mm. Annual precipitation over the canopy projection is 300 mm/year [7]. In computations based on [7] we assumed that 85% of precipitation in both zones (canopy-covered and bare) goes for transpiration. For the selected crown radius this gives 1750 liters/year/tree under the canopy. For comparison, the most common fruiting tree in the region, date palm, consumes 30–50 thousand liters of water through regular irrigation. Most of the water uptake in the Dhofar forest occurs after the end of the monsoon until a certain instance when water becomes limiting and transpiration decays [7]. It is noteworthy that irrigation of date palms and other crops requires thorough scheduling over season with the range of irrigation 50–150 l/day (winter–summer) that is time, labour and instrument consuming. The natural forest does self-irrigation spontaneously.

The following balance equation holds:

$$\int_0^{365} Q(t)dy = 1.75 \text{ m}^3$$

wherefrom we calculated e_0 assuming different values of α. Experimental data for α are not available for our trees. Along with the exponentially decreasing uptake – depth function other «integrable» functions can be included into the model, for example, linear ones as in [21].

In Fig.4 the fronts y_i and y_d are shown as functions of t in the interval 0<t<365 days for a cyclostationary sink with $f(t)=\sin^2(\omega t)$, $\omega=2\pi/182.5$ 1/day. We solve eqns. (9)–(10) as a Cauchy problem using a standard Runge-Kutta **NDSolve** routine of computer algebra [23].

We fixed y_0=0.6 m and selected α=0.1 (e_0=0.00064) and α=2 1/m, (e_0=0.013). Curves 1 and 2 correspond to the imbibition fronts and curves 3–4 indicate the drainage fronts for these two α values. As we can see from the graphs, the fronts decelerate with fluctuations (the slugs shrink). Our computations also showed that with the increase of the initial slug thickness its migration rate increases. Hydrological implications of this dynamics are clear: in Darcian flows inertia is neglected [17] and therefore the motion of two consequitive slugs can be studied by specifying their initial positions only. If a larger «new» slug moves faster it may catch up a smaller one. Tehn two slugs merge and move even faster to the water table.

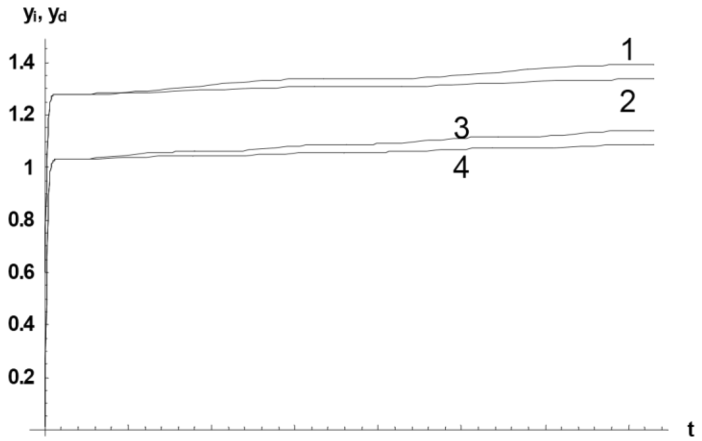


Fig.4. Dynamics of fronts for two different α

Discussion and Conclusion

Soil moisture distribution and its dynamics in the soil profile are vitally important for the flora in WLE. Cloud forests in arid/semi-arid climates of the Arabian peninsula in the Dhofar region of Oman live in unique hydrological niches. The forest in this region is highly susceptible to variations of the precipitation fluxes, which are characterized by a 3-month long monsoon duration and annual cyclicity. Precipitation consists of two components: (1) Orographic low-intensity rain (drizzle) and (2) fog collection (turbulent deposition of cloud droplets). Fog collection leads to heterogeneous infiltration: Under tree canopies infiltration is estimated to be twice as high, compared to the off-canopy surroundings. The latter leads to temporary and radially varying compartmentalization of water in the root zone.

The forest-enhanced precipitation stimulates the biota and possibly contributes to the recharge of the water table. Net precipitation under the tree canopies has been estimated to be around 300 mm over the entire 2004 monsoon season. The transient subsurface storage accumulated during the monsoon is consumed later by evapotranspiration (net ascending flux) and is composed of the gravitational, capillary and viscous (Darcian) forces (net descending flux). In this paper we predict how much out of the 300 mm net precipitation might reach the aquifer, provided the water uptake by the tree roots varies with depth and time that results in a «trough-shaped» moisture profiles with depth.

We considered the monsoon-generated soil moisture volume as a shrinking parcel, which travels through the vadose zone, and implemented the Green-Ampt type model on the scale of a near-trunk cylindrical porous column. Water motion is characterized by two fronts (drainage and imbibition) and soil water removal by the roots. The advancing front flux is greater than the retreating one. The ordinary differential equations for the front loci are solved numerically, and the possibility of water table recharge is estimated.

If the slugs reach the water table, then groundwater mounds (axisymmetric with respect to the tree roots) emerge and decay cyclostationary. The possibility for the deep tree roots to be immersed into the capillary fringe should be assessed in the future. If the forest is approximated as a regular (e.g., chess-board) pattern of trees without interference of adjacent trunkcentered moisture parcels, then the catchment-scale recharge of the aquifer can be evaluated, in particular, the effect of a partial uphill deforestation (for example due to cattle browsing or infections) on the drop of the groundwater level and hence capillary fringe. The latter may induce further stress on phreatophytic species in the downhill zone.

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ВЛИЯНИЕ СКЛОНОВОГО ЛЕСА ОМАНА (РЕГИОН ДОФАР), ПИТАЕМОГО ОСАДКАМИ ИЗ ТУМАНА, НА ПОДЗЕМНЫЙ ГИДРОЛОГИЧЕСКИЙ РЕЖИМ: МОДЕЛИРОВАНИЕ В МАСШТАБЕ КОРНЕВОЙ ЗОНЫ

Рассматривается склоновый лес полуаридной зоны в Омане, особенностью которого является перехват кроной деревьев жидкости (тумана и осадков слабой интенсивности) из муссонного ветра в течение трех месяцев в году. Эта вода капает с листвы на землю по площади проекции кроны и стекает по стволу, в результате чего влага аккумулируется в прикорневой зоне почвы и используется деревом в течение длительного постмуссонного периода. За счет капиллярности и гравитации почвенная вода дрейфует к зеркалу грунтовых вод. Предложена модифицированная математическая модель Грина-Ампта для вертикального влагопереноса в зоне питания дерева, которая учитывает циклостационарность процесса «капельного самоорошения», неравномерный по глубине перехват влаги распределенными корнями дерева и возможность остановки движения воды за счет неодинаковых капиллярных давлений в зоне промачивающего и дренирующего фронтов.

Ключевые слова: *листопадный туманный лес, засушливый/полузасушливый регион, склоновая растительность, орографический дождь, забор влаги корнями растений, закон Дарси, модель Грина-Ампта.*

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