Supplement 1: Model Equations

1 Plot scale vadose zone model

The 1D water balance was computed by coupling the multiple wetting front model [*Struthers et al.*, 2006] to an estimate of potential evaporation made using the Hargreaves Equation and crop coefficients. Crop coefficients were obtained from FAO [*Allen et al.*, 1998].

The Hargreaves Equation performs comparably well to the Penman Monteith equation in estimating reference evaporation conditions over periods of time exceeding 5 days [*Hargreaves and Allen*, 2003]. The MWF model is a kinematic wave approximation to Richards equation. It has been validated against the full solution to Richards equation and lysimeter data (Struthers et al., 2006), and when coupled with an appropriate potential evaporation representation, reproduced temporal patterns of shallow soil moisture availability from multiple Ameriflux sites with an RMS error of 2.5% water content, and observed seasonal variations in transpiration with a mean error of 17%, which lies within the typical error in the observations eddy covariance energy balance closure [*Thompson et al.*, 2011].

Having prescribed potential evaporation, actual evaporation during any given time-step was computed based on peak soil moisture availability (i.e.the maximum value of the volumetric water content, θ) across a root system with rooting depth r_z (m). This assumes that there is sufficient plasticity in the root system to supply evaporative demand at the leaves with water resources located anywhere in the rooting zone.

Given this peak soil moisture availability, actual evaporation was computed as:

$$ET = EP\frac{\theta - \theta_w}{\theta^* - \theta_w} \tag{1}$$

This allows evaporation to vary linearly between the threshold for complete stomatal opening (θ^*) and complete stomatal closure, or the wilting point (θ_w). To account for the potential for eucalyptus plantations to also âĂIJmineâĂİ deeper water reserves, we also ran a scenario that incorporated a phenomenological treatment of such uptake from a saturated zone. This altered Equation 1 to read:

$$ET = EP \times max\left\{\frac{(\theta|_{(min,gw)} - \theta_w)}{(\theta^* - \theta_w)}, \frac{(\theta - \theta_w)}{(\theta^* - \theta_w)}\right\} \tag{2}$$

Effectively, if the soil column becomes drier than an assumed water supply due to capillary rise over a saturated zone, parameterized as $\theta|_{(min,gw)}$, then ET is supplied by this minimum water flux from the saturated zone. We set $\theta|_{(min,gw)}$ to 0.25 for all runs.

MWF was run for two homogeneous soil types, with properties derived from textural observations at two soil pits and used to estimate soil hydraulic properties (K_{sat}, porosity, θ_w, θ^* and field capacity θ_{fc}) via a pedotransfer function [*Saxton and Rawls*, 2006]. The model was run over the one-dimensional domain set by the root depth for each land cover type.

The MWF Model generated the following outputs for each 30-min interval: runoff (RO_l), evapotranspiration (ET_l), any lateral discharges, deep drainage (RCH_l), and, for the eucalyptus runs, the portion of evapotranspiration supplied by groundwater uptake ($EucGW_l$) for each land use category l. These were aggregated to the monthly time step m.

For land use categories which are irrigated (double cropped area, perennial irrigated, irrigated field crops and rice), we assumed that the difference between potential evapotranspiration for that crop and actual evapotranspiration was met by irrigation, $IWR_l(m)$.

Table 1. Soil Parameters in MWF Model

Soil Parameter	Value	Source
Porosity n	0.41	
Wilting point θ_w	0.22	
Stomatal opening point θ^*	0.32	
Field capacity θ_{fc}	0.32	
Sat. Hydraulic Conductivity K_{Sat}	6 mm/hr	
Min. Water Content $\theta\|_{(min,gw)}$	.25	

$$IWR_l(m) = PET_l(m) - ET_l(m) \tag{3}$$

Since the term irrigation water efficiency is usually defined with respect to crop yields, we use the term irrigation sagacity [*Burt et al.*, 1997] as the ratio of the irrigation water requirement needed to satisfy the crop's beneficial water needs to the actual water abstracted. Irrigation sagacity was a calibrated parameter in the model shown in Fig. 5.

$$IS(m) = IWR_l(m) \div WE_l(m) \tag{4}$$

The abstraction was apportioned between groundwater and surface water based on known sources of irrigation (Fig 5).

$$GWE_l(m) = WE_l \times GW_{frac}(m) SWE_l(m) = WE_l \times SW_{frac}(m) \tag{5}$$

2 Tank scale model

2.1 Tank scale surface water model

Runoff, recharge, evapotranspiration and groundwater abstraction obtained at 30 min intervals from the MWF model were aggregated to the tank scale for each time period by multiplying by the area under each of the 13 land uses for each tank k, in TG Halli catchment.

$$RO_k(m) = \sum_{l=i}^{l=13} RO_l(m) \times Area_{kl}(m) \tag{6}$$

$$RCH_k(m) = \sum_{l=i}^{l=13} RCH_l(m) \times Area_{kl}(m) \tag{7}$$

$$ET_k(m) = \sum_{l=i}^{l=13} ET_l(m) \times Area_{kl}(m) \tag{8}$$

$$EucGW_k(m) = \sum_{l=i}^{l=13} EucGW_l(m) \times Area_{kl}(m) \tag{9}$$

RO_k, RCH_k and ET_k represent the total runoff, recharge and ET generated for the tank sub-watershed in month m. $Area_{kl}$(m) is the area in the sub-watershed of tank k, that was under land use l in month m.

The runoff obtained from MWF was trapped in farm bunds and check dams. The volume of decentralized storage under farm bunds FB_k(m), and check dams CD_k(m), were calibrated parameters (Fig. 5). Runoff generated within the watershed of each tank could be impounded behind these structures. Once these storage structures were filled, any excess runoff was routed as inflows into the tank $TankRO_k$(m). It was thus assumed that there was no carry over storage across months in these decentralized storage structures.

$$VI_k(m) = Min\left\{RO_k(m), FB_k(m) + CD_k(m)\right\} \tag{10}$$

$$TankRO_k(m) = RO_k(m) - VI_k(m) \tag{11}$$

Of the water impounded, 20% was assumed to evaporate and 80% was assumed to infiltrate based on the empirical observations from check dams. The infiltrated volume from farm bunds and check dams was proportionately allocated between recharge and ET.

The excess runoff (not impounded) flowed into the tank. The generalized storage-area relationship for the tanks allowed conversion of storage volume to waterspread area $TankWA_k(m)$ for each month. By plugging in the observed recharge rate for tanks of 0.0125 mday^{-1} and monthly evaporation rates we could compute the monthly tank evaporation of $TankE_k(m)$ and tank bed recharge of $TankRCH_k(m)$.

$$TankWA_k(m) = f\left\{TankSt_k(m)\right\} \tag{12}$$

2.2 Tank scale ground water model

Baseflow BF_k was assumed to be generated if the groundwater depth GD_k in the aquifer was less than some threshold $GD_{Threshold}$ and was determined by the groundwater discharge rate α, a calibrated parameter that was set at 0.2. We assumed the threshold to be 10 m below ground level. However, the model was not very sensitive to this parameter. The effect of monthly recharge and abstraction swamped the effect of groundwater discharge rate to the stream.

If $GD < GD_{Threshold}$

$$BF_k(m) = \alpha \times (GD_{Threshold} - GD_k) \tag{13}$$

Now the groundwater balance for each tank aquifer could be used to estimate the change in groundwater storage underneath each sub-watershed $\Delta GW_k(m)$.

$$GW_k(m) - GW_k(m-1) = RCH_k(m) + TankRCH_k(m) - GWE_k(m) - EucGW_k(m) - BF_k(m) \tag{14}$$

Change in groundwater depth was assumed to be based on

$$GD_k(m) - GD_k(m-1) = \Delta GW_k(m) \div S_y \tag{15}$$

3 Watershed scale model

The tanks in the TG Halli watershed form a cascading network. Thus a given tank in the series may receive overflow from an upstream tank $TankUS_k(m)$ in addition to inflows from its own watershed. Outflows from tank include evaporation, recharge from the tank bed and direct abstraction for tank irrigation. If the tanks inflows and outflows, cause it to exceed the maximum storage $TankMaxSt_k$, it will overflow. Because this model is being run on a monthly time step, the excess volume is immediately transferred to the downstream

Table 2. Parameters used in multi-scale simulation model

Scale	Parameter	Source of Data
Plot	Soil Parameters 30-min Rainfall Crop coefficients Irrigation water use efficiency	Infiltration experiments, calibrated parameter Downscaled from daily data FAO published data Estimate obtained from survey of all irrigated plots in milli-watershed (current) extrapolated to the upper Arkavathy, Calibrated (historical)
Tank	Check dam density and volumes Farm bund coverage and heights Aquifer characteristics Borewell density	Field surveys and check dam bathymetry were used to derive generalized stage-area and stage-volume relationships Calibrated parameter Borewell camera scan data in milli-watersheds used to derive specific yield. Assumed uniform for whole watershed Well census
Watershed	Tank area and volumes	Drone and boat based bathymetric surveys used to derive generalized stage-area and stage-volume relationships

tank. Our observations from instrumented tanks within the city of Bengaluru (where such cascading is common) shows that the overflow events typically last a few days after major storms.

The overflow from each tank spills into the downstream tank; i.e., so it becomes the upstream flow for the tank immediately downstream. As long as we start from the upstream most tank and move downstream, the water balance for each consecutive tank can be solved.

$$TankIN_k(m) = TankRO_k(m) + TankUS_k(m) \tag{16}$$

$$TankOUT_k(m) = TankRCH_k(m) + TankE_k(m) + SWE_k(m) \tag{17}$$

$$Spill_k(m) = Max\left\{(TankSt_k(m-1) + TankIN_k(m) - TankOUT_k(m) - TankMaxSt_k), 0\right\} \tag{18}$$

$$TankSt_k(m) = TankSt_k(m-1) + TankIN_k(m) - TankOUT_k(m) - Spill_k(m) \tag{19}$$

Groundwater balance at the TG Halli scale was merely aggregated from the tank-scale groundwater balance as groundwater connectivity between the sub-watersheds was assumed to be insignificant.

A list of all parameters is presented in the Table below.

References

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