Agricultural Water Management 58 (2003) 171–192

Agricultural
water management

www.elsevier.com/locate/agwat

Water balance variability across Sri Lanka for assessing agricultural and environmental water use

W.G.M. Bastiaanssen[a,*], L. Chandrapala[b]

[a]International Water Management Institute (IWMI), P.O. Box 2075, Colombo, Sri Lanka
[b]Department of Meteorology, 383 Bauddaloka Mawatha, Colombo 7, Sri Lanka

Abstract

This paper describes a new procedure for hydrological data collection and assessment of agricultural and environmental water use using public domain satellite data. The variability of the annual water balance for Sri Lanka is estimated using observed rainfall and remotely sensed actual evaporation rates at a 1 km grid resolution. The Surface Energy Balance Algorithm for Land (SEBAL) has been used to assess the actual evaporation and storage changes in the root zone on a 10-day basis. The water balance was closed with a runoff component and a remainder term. Evaporation and runoff estimates were verified against ground measurements using scintillometry and gauge readings respectively. The annual water balance for each of the 103 river basins of Sri Lanka is presented. The remainder term appeared to be less than 10% of the rainfall, which implies that the water balance is sufficiently understood for policy and decision making. Access to water balance data is necessary as input into water accounting procedures, which simply describe the water status in hydrological systems (e.g. nation wide, river basin, irrigation scheme). The results show that the irrigation sector uses not more than 7% of the net water inflow. The total agricultural water use and the environmental systems usage is 15 and 51%, respectively of the net water inflow. The consumptive use of rain-fed and irrigated agriculture are approximately equal. The evaporation rates in agriculture and mixed vegetation are similar, so that low productivity rangelands can be transformed into rain-fed agriculture without detrimental effects on water availability to downstream users. The unused water flow to the Indian Ocean is 34% of the net inflow, hence there is scope for further water developments in Sri Lanka.

Keywords: Agriculture; Environment; Water use; Water availability; Remote sensing; Sri Lanka

---

[*] Corresponding author. Present address: International Institute for Aerospace Survey and Earth Sciences (ITC), P.O. Box 6, 7500 AA, Enschede, The Netherlands. Tel.: +31-53-4874233; fax: +31-53-4874336.
E-mail addresses: w.bastiaanssen@itc.nl, w.bastiaanssen@waterwatch.nl (W.G.M. Bastiaanssen).

PII: S0378-3774(02)00128-2

1. Introduction

Over the past decades, food production has kept pace with soaring populations, but how long will this last? A competition between water use groups has started in large parts of the world, and the water demand may exceed the water availability to feed thirsty crops (Seckler et al., 1998). Many of the world's river basins—even under humid conditions such as in Sri Lanka—are faced with a physical water shortage. In spite of the importance of water resources management, the available database of information on water use in agriculture and about the amount of water consumed by environmental systems is totally inadequate. Environmental systems are referred to as all natural vegetation systems not planted by man, including natural heritages such as wetlands and wildlife reserves. The recently established world dialogue on water for food and environmental security stated, "achieving water security for the sustainable production of food and rural livelihoods while maintaining or improving the quality and biodiversity of the natural resources and eco-systems is one of the key challenges of the early 21st century " (Anonymous, 2000a). The key question is how to achieve such an environment without basic water resources data? An additional aspect is that the knowledge on water demand, water use and water availability in natural ecosystems lags behind the pool of science developed for water in agriculture. Information tools therefore need to be developed which, for data sparse environments, give rapid assessment of the water status in river basins for strategic planning.

All the users are hydrologically linked in a river basin and re-allocation of water—including water savings on irrigated land—has by definition impacts on the other users. Upstream developments such as deforestation, irrigation modernization, increased urbanization and industrialization have effects on the downstream riparian zones. Environmentally endorsed activities—which sound eco-friendly in the first instance—may have adverse effects on environments elsewhere in the system: stimulating agro-forestry to enhance biodiversity and reduction of soil erosion in the upstream part of the basin can lead to extermination of flora and fauna in, for instance, the coastal zone region. Misuse and misallocation of good quality water damages the arable land resources through salinization or water-logging and can threaten other eco-systems and wetlands. A well-balanced partitioning of fresh water resources into agriculture and natural eco-systems is a primary concern for all. Agricultural water management has therefore to broaden its scope and seek quantitative solutions to live "peacefully" with other users at the river basin context. Bouwer (2000) has further added issues of non-source pollution from agriculture to other concerns about water quality deterioration.

The IWMI paradigm (Perry, 1998) promotes an approach that links sources, uses, losses and re-uses by different land use categories and vegetation zones occurring within the river basin context. The relationship between land use, water use and water supply must be described quantitatively, however this is not straightforward due to the natural heterogeneity and complexity of hydrological processes in catchments. The aim of this paper is to demonstrate that remote sensing techniques can be an efficient way of providing key information on water availability and water use in agricultural and environmental systems. The data has been explored further to evaluate the efficiency of water use at national scale in Sri Lanka using IWMI's water accounting framework (Molden, 1997; Molden and Sakthivadivel, 1999).

2. Material and methods

Sri Lanka consists dominantly of a crystalline basement complex. Groundwater systems are less developed. The hard rock region of Sri Lanka covers about 80% of the island. Only the coastal belt of alluvial deposits and miocene limestone in the north and northwest contains highly productive aquifers. The pattern of land use has been changing fairly rapidly in Sri Lanka over the past centuries. In 1800, the population was small and forest covered most of the island. Clearing up the forests for plantation agriculture was the greatest change that took place in the 19th century. In 1901, the forest cover was 70% and this has dwindled to 24% in 1996. Sri Lanka contains different types of forest as explained in Table 1. The moist monsoon forests are exposed to a rainfall peak from October to January followed by a dry period of about 3 months. The dry monsoon forests occur where there is a pronounced dry period of 3–6 months. The sub-montane forests are found in the hill country where temperature is between 15 and 20 °C. Riverine forests are typically located along river valleys and permanently wet flood plains. Sparse forests have an open structure and can be categorized as bushland. The major agricultural crops are rice fields (i.e. paddy), tea, rubber and coconut. Rice is usually irrigated, although some rain-fed rice cultivation is practiced. Plantations are located in rainfall zones suitable for good tree development without supplementary irrigation. Sri Lanka is among the largest tea exporters in the world. The land use data in the current research study is taken from the Arjuna's atlas of Sri Lanka (Somasekaram et al., 1997).

The rainfall distribution in Sri Lanka is influenced by monsoons, the inter tropical convergence zone (ITCZ), convection, orography, easterly waves and cyclonic wind circulations. The rainfall measurement network in Sri Lanka is presented in Fig. 1. It consists of just over 400 individual rainfall gauges, with the majority being located in the southwestern part of the island coinciding with the area of highest rainfall rates. Point measurements of rainfall have been extrapolated to a raster map with a 1 km grid separation by means of ordinary kriging technique. First, the 10-day totals of the individual rain gauges were collected and entered as a point map in a GIS. Thereafter, the gridding was performed. The delay between field observation and processing of the rainfall data during the study period (June 1999–2000) was approximately 3 weeks.

Water use evaluations in this paper are based on the actual evaporation figures presented by Chandrapala and Wimalasuriya (2003). The computations of evaporation are based on NOAA-AVHRR satellite data using the Surface Energy Balance Algorithm for Land

Table 1
Characteristics of the major forest types of Sri Lanka

Forest type	Elevation (m)	Precipitation (mm per year)
Moist monsoon forest	<1000	1800–2500
Sub-montane forest	1000–1500	>1800
Dry monsoon forest	<600	900–1500
Lowland rain forest	<1000	>2500
Riverine dry forest	<600	900–1500

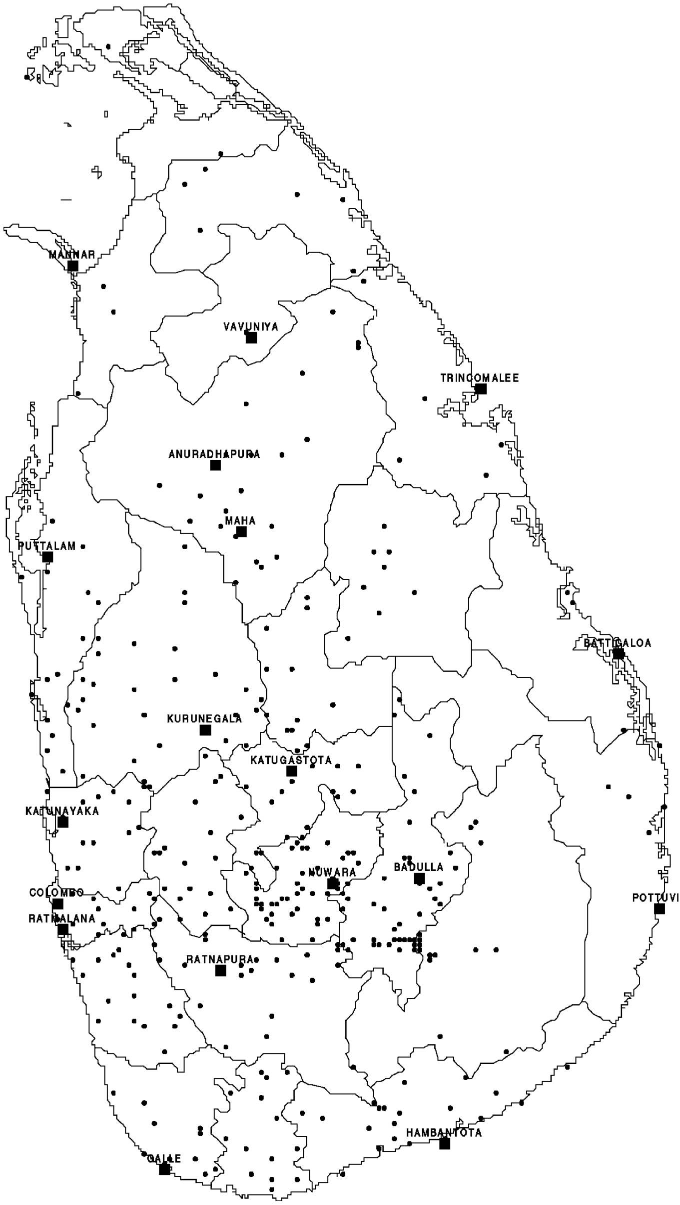

Fig. 1. Rain gauge network across Sri Lanka overlain with the districts.

(SEBAL). The rainfall surplus (S_p, cm) for every pixel is taken as the difference between rainfall P and actual evaporation, ET_{act}:

$$S_p = P - ET_{act} \tag{1}$$

Traditionally, river runoff is computed from rainfall events, soil properties, antecedent moisture and vegetation cover using empirical relationships such as the soil conservation service curve number method (Schaake et al., 1996). These relationships are based on an average hydrological behaviour assuming a certain amount of water to be stored and evaporated by vegetation. Changing land use patterns or presence of diversion dams for allocating water to irrigation schemes affect runoff computations significantly, and such changes are not generally reflected in these types of empirical expressions. A simple and novel approach is therefore suggested; The incorporation of $\mathrm{ET_{act}}$ directly into the water balance enabling computation of river runoff as the rainfall surplus S_p corrected by a storage term for water infiltrated into the unsaturated zone:

$$R = S_\mathrm{p} + \Delta W_\mathrm{unsat} \tag{2}$$

where R (cm) is the surface runoff. The storage term ΔW_unsat (cm) reflects the soil moisture status of the unsaturated zone being a result of infiltration, evaporation and percolation processes, and can be further defined as:

$$\Delta W_\mathrm{unsat} = \int_0^{100} \theta(z, t + \Delta t)\,\mathrm{d}z - \int_0^{100} \theta(z, t)\,\mathrm{d}z \tag{3}$$

where, θ ($\mathrm{cm^3\,cm^{-3}}$) is the volumetric soil water content, z (cm) the depth and t (days) the time. The soil moisture in Eq. (3) is integrated between surface level and 100 cm depth to account for the moisture changes in the root zone. It is recognized that trees usually root deeper, but the 100 cm depth is considered a reasonable average for trees, crops, lakes and areas with very shallow soils on rocky sub-stanta. There are no remote sensing techniques available to determine the moisture variation with depth, $\theta(z)$ and Eq. (3) has therefore been simplified into:

$$\Delta W_\mathrm{unsat} = \theta_\mathrm{avg}(t + \Delta t)100 - \theta_\mathrm{avg}(t)100 \tag{4}$$

where θ_avg is the moisture content averaged for the depth interval between 0 and 100 cm. This root zone moisture value can be determined from:

$$\theta_\mathrm{avg} = \frac{\theta_\mathrm{sat}}{0.51}\exp\left\{\frac{[\lambda E/(\lambda E + H)] - 1.28}{0.421}\right\} \tag{5}$$

where θ_sat ($\mathrm{cm^3\,cm^{-3}}$) is the soil water content at saturation, i.e. the soil porosity for a particular soil. Eq. (5) is based on the partitioning of the sensible H and latent heat fluxes λE (Bastiaanssen et al., 2000). A latent heat flux higher than the sensible heat flux is associated with moist soils and vice versa.

Eq. (2) may work well for limited areas where groundwater interactions and surface water storage phenomena are of minor importance. Under these circumstances, runoff may be regarded as the water balance closing term. If part of the runoff is stored in reservoirs and subsequently used to irrigate crops, evaporation is enhanced and this phenomenon will be “picked-up” by the satellite based estimation of evaporation. In case a larger volume of water is stored in the reservoir than being released for irrigation practices, R cannot be simply regarded as the difference between S_p and ΔW_unsat, hence Eq. (2) is not always valid for regulated rivers. Eq. (6) needs to be introduced to describe an additional storage/supply

G-term that regulates river flow:

$$G = P - ET_{\mathrm{act}} + \Delta W_{\mathrm{unsat}} - R \quad (6)$$

where G (cm) represents:

- uncertainty in P, ET_{act}, and $\Delta W_{\mathrm{unsat}}$;
- storage changes in tanks and reservoirs due to regulated river flows;
- storage changes in ground water;
- inter-basin water transfer through pipelines;
- inter-basin groundwater flow;
- seawater intrusion;

3. Hydrological analysis

3.1. Water balance at national scale

During the study period from June 1999 to 2000, the annual average rainfall over the island was 1751 mm, whereas the country average value for 1961–1990 is 1861 mm. Hence, it was a below-average rainfall year (6.3% less). The annual rainfall isohyets are presented in Fig. 2. The largest quantity of rain in Sri Lanka occurs on the western slopes of the central highlands with quantities exceeding 4000 mm per year. The average annual rainfall in this area is between 4000 and 5000 mm with a peak of 5330 mm per year at Maliboda (6°52.9′N, 80°25.9′E) rain gauge station. The peak during June 1999–2000 was 4950 mm per year (Fig. 3), and this was registered near Maliboda. The northern half of the country is generally referred to as the dry zone and the climatological average annual rainfall lies between 1000 and 1500 mm. The lowest rainfall during the study period occurred near Mannar in the northwest with values slightly under 750 mm per year. For compatibility with the NOAA-AVHRR images for actual evaporation and soil moisture, rainfall measured at points has been converted to a regular grid of 1 km.

The accuracy of satellite based evaporation mapping techniques was verified for a mixture of paddy fields and coconut palm trees over a distance of 2 km near Horana in southwestern Sri Lanka by Hemakumara et al. (2003). They found the deviation between evaporation estimates from the SEBAL remote sensing technique and in situ measurements with a large aperture scintillometer (De Bruin et al., 1995) on 10-day basis to be 17% and on monthly basis to be 1%. This type of uncertainty agrees with earlier comparisons of SEBAL against eddy correlation, Bowen ratio and scintillometer measurements in environments ranging from deserts to irrigated oases and river valleys (Wang et al., 1995; Bastiaanssen et al., 1998; Kite and Droogers, 2000). Earlier comparisons showed no systematic bias of SEBAL performance with respect to land wetness. This suggests that it should not be expected that SEBAL performs worse in the dry zone of Sri Lanka as compared to the wet zone. Since the evaporation estimates in Sri Lanka could only be verified against scintillometer measurements installed over the vegetation types prevalent in Horana, there is no guarantee that the performance is equally good for all land use classes. It should be noted that the overall accuracy of SEBAL for 10-day periods depends

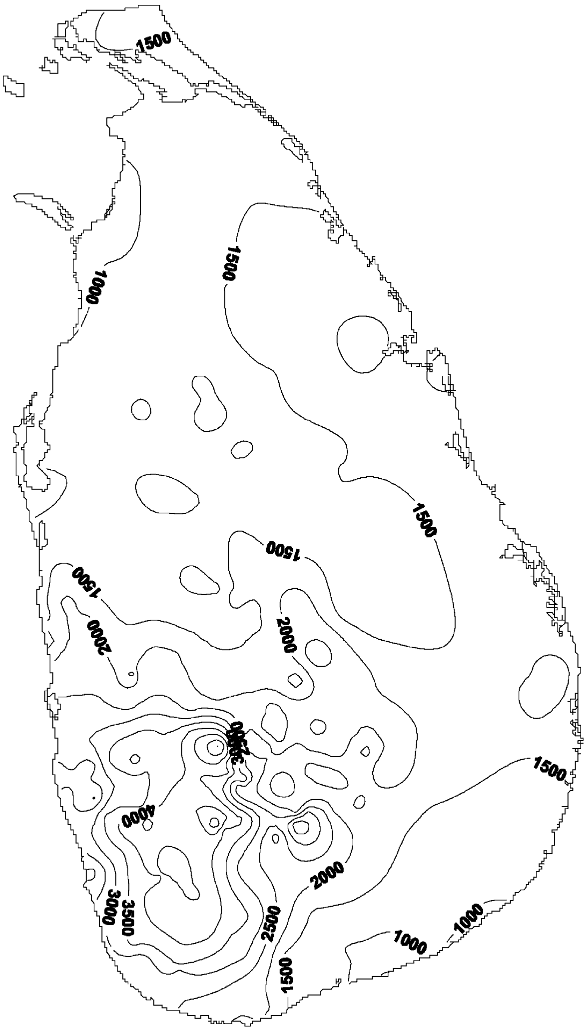

Fig. 2. Spatial variation of the annual rainfall between June 1999 and 2000 interpolated from individual rain gauges using ordinary kriging techniques and interpreted to isohyetes.

under these humid conditions on the interpretation of cloud cover data. The daily sunshine hours were estimated from a network consisting of 20 stations.

Existing land use and forest maps from Somasekaram et al. (1997) were superimposed on the NOAA-AVHRR based evaporation images. Some land use categories were not classified, and this resulted in a large area classified as mixed vegetation. The analysis showed evaporation rates as low as 360 mm per year on limestone outcrops in the Jaffna peninsula to as high as 1889 mm per year in a large open water reservoir (Padawiya tank) in the Anuradhapura district. The evaporation of land surfaces did not exceed 1687 mm per year, which occurs in a moist area in the dry monsoon forest in the northwestern Mannar

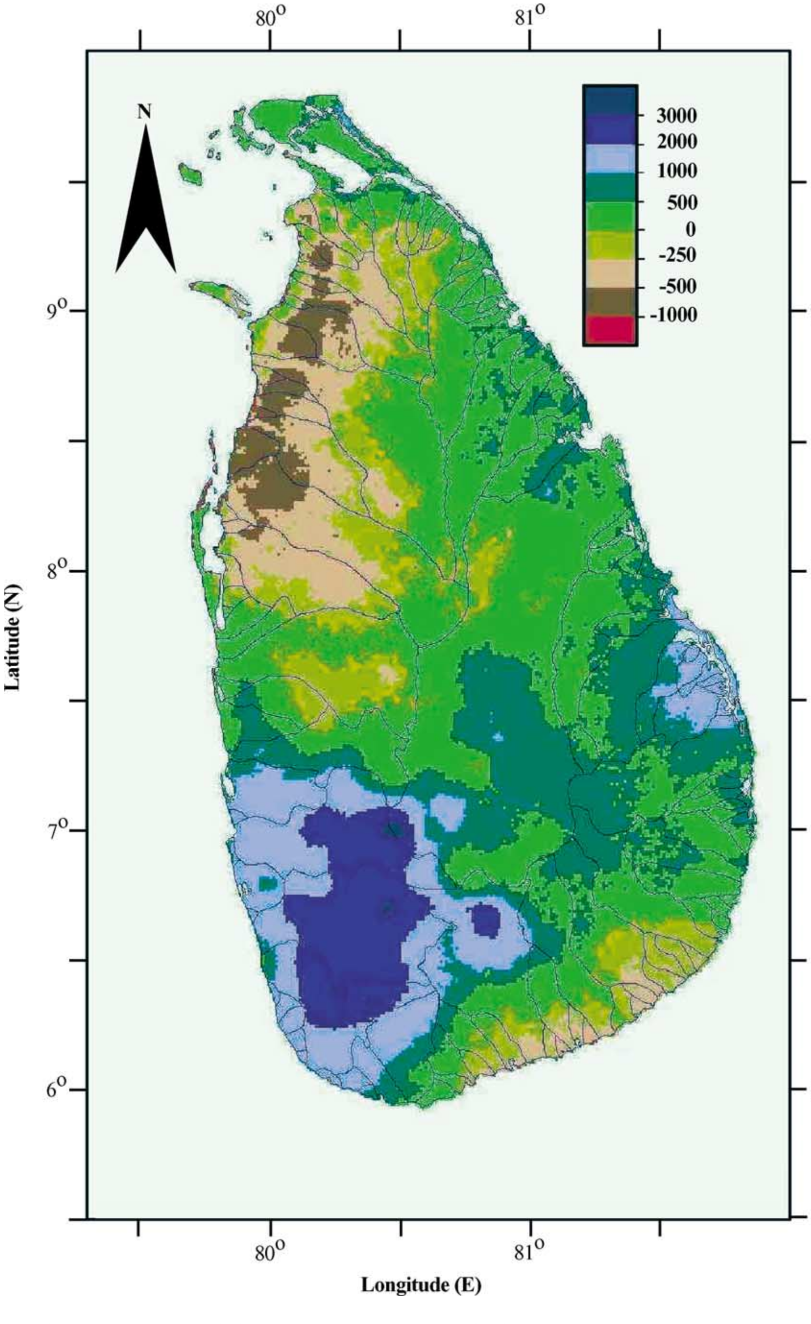

Fig. 3. Rainfall surplus (gross rainfall − actual evaporation) of Sri Lanka between June 1999 and 2000 with the boundaries of all river basins superimposed.

Table 2
Nation wide breakdown of annual actual evaporation of Sri Lanka

Land cover	Area (km^2)	Evaporation (mm per year)	Evaporation (Mm^3)	Evaporative depletion (%)
Tea	2,569	1246	3,201	3.8
Rubber	2,295	1341	3,078	3.7
Coconut	2,945	1335	3,932	4.7
Paddy	7,815	1226	9,581	11.4
Moist monsoon forest	2,923	1263	3,692	4.4
Sub-montane forest	796	1240	987	1.2
Dry monsoon forest	10,613	1407	14,933	17.8
Lowland rain forest	1,796	1319	2,369	2.8
Sparse forest	4,772	1247	5,951	7.1
Riverine dry forest	534	1348	720	0.9
Mixed vegetation	28,325	1245	35,434	42.0
Total	65,383	1279	83,806	99.8

district. The weighted average evaporation for all classes is 1279 mm per year. The actual evaporation varies among different land use categories. Forests evaporate 1337 mm per year, with a range between 1240 mm per year for sub-montane forests to 1407 mm per year for dry monsoon forests (see Table 2). The country average evaporation of 1279 mm per year is in good agreement (2% difference) with earlier results found in the Kirindi Oya watershed, where the average evaporation for mixed vegetation was estimated as 1306 mm per year (Renault et al., 2001). Actual evaporation in the latter case was estimated as the residual term of a catchment water balance.

The dense dry monsoon forests are located in the northern and northwestern parts of the country, and these areas with a high evaporative depletion coincide with the presence of shallow aquifers. These forests stand in a seepage zone and probably extract water directly from the shallow groundwater system. Despite rainfall in this part of the country being lower than average (see Fig. 2), the dense forests are, with an annual evaporation at 1407 mm per year, not greatly water stressed. The explanatory reason is that several parallel basins recharge the coastal zone aquifer systems. It is likely to be a location where groundwater is abundant and supports vigorous tree growth. An independent verification for this particular area was made by involving the water use efficiency (biomass/actual evaporation). Following Choudhury (1997), published water use efficiency values for rain forests, closed boreal forests and mixed forests are 2.10, 2.10 and 2.0 kg m^{-3}, respectively. Muthuwatta and Chemin (2003) demonstrated that the average annual biomass production of dry monsoon forest is 27,820 kg ha^{-1} per year, which for the given water use efficiencies yield actual evaporation rates of approximately 1325, 1325 and 1391 mm per year. This is in good agreement with the 1407 mm per year evaporation estimates found from SEBAL.

Table 2 indicates that paddy fields consume 11.4% of the total evaporation. Although rain-fed paddy farming is practiced in Sri Lanka the real extent is limited. All paddy cropping is for sake of simplicity schematized to be part of irrigated agriculture. The mixed vegetation also includes a wide variety of land use types, including un-vegetated limestone, surface water storage tanks and sand dune areas. Since the evaporation of crops and of mixed vegetation is similar, it can be concluded that land use changes from rangeland with mixed vegetation into, for instance, rain-fed agriculture will not have significant effects on the surplus, at least not on an annual basis.

The rainfall surplus map was used to investigate the redistribution of water within each basin. Pixels with a positive rainfall surplus are typically discharge areas contributing to runoff or to groundwater recharge. These areas are often found near the upstream end of the basin, but can also occur downstream, if vegetation is sparse leading to reduced evaporation. Pixels with a negative surplus consume more water than being supplied through local rainfall and generally occur at the downstream end of the basins. These pixels typically lay in recapturing and seepage zones, where groundwater systems are shallow. Perennial vegetation may tap the groundwater systems directly, or indirectly through capillary rise. A negative surplus also occurs in irrigation schemes constructed to increase the natural low in situ evaporation. This study indicates that 22% of the land area of Sri Lanka has a negative surplus, suggesting water recapture occurs in 22% of the island. The average negative surplus at a 1 km scale is—262 mm with a standard deviation of 187 mm. It should be noted that small 1 km areas with a negative surplus of −262 mm are under the influence of local hydrological process which are irrelevant at national scale.

The spatial pattern of rainfall surplus has a relationship with land use and vegetation zones (Table 3). Most surplus water in Sri Lanka occurs in the lowland rain forest—the southwest wet zone—and in the rubber plantations, mostly found in the same region. Hence, abundant rainfall is more the cause for the spatial variability of surplus, than evaporation. Highland tea estates and sub-montane forests also contribute to surplus and the generation of river runoff. The dry monsoon forests consume more water annually (−62 mm per year) than is being produced by runoff.

Surface runoff, as defined in Eq. (2), is computed for all river basins of Sri Lanka at monthly time steps. The equation is applied to mean rainfall and mean evaporation for the entire river basin. Short-term changes of water storage in the topsoil at basin level ($\Delta W_{\mathrm{unsat}}$) have been computed each month assuming a rooting depth of 1 m. ‘‘Ganga’’ is a local term

Table 3
Land use wise rainfall surplus in Sri Lanka

Land cover	Precipitation (mm per year)	Evaporation (mm per year)	Surplus (mm per year)
Tea	2348	1246	1102
Rubber	3176	1341	1835
Coconut	1594	1335	258
Paddy	1665	1226	439
Moist monsoon forest	1693	1263	430
Sub-montane forest	2364	1240	1124
Dry monsoon forest	1345	1407	−62
Lowland rain forest	3254	1319	1935
Sparse forest	1399	1247	152
Riverine dry forest	1447	1348	99
Mixed vegetation	1745	1245	500
Average	1751	1279	472

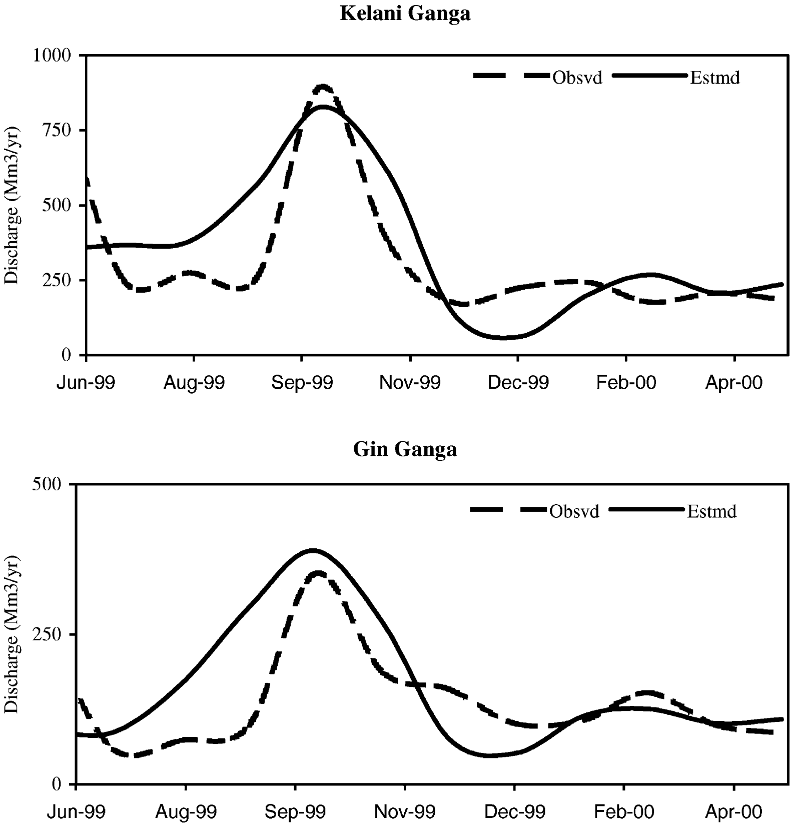

Fig. 4. Observed and remote sensing computed monthly hydrographs of Kelani Ganga and Gin Ganga between June 1999 and 2000.

for perennial rivers whereas others (Oya) fall dry during certain periods of the year. The monthly runoff values resulting from Eq. (2) have been smoothed by a moving average of 3 months to take into consideration the slow baseflow response to rainfall events of Ganga's. A negative runoff after smoothing will be set to zero, and a rest term is taken to conserve the balance. An example of the monthly hydrograph and the agreement with observations is presented in Fig. 4 for two selected basins.

The root mean square errors (RMSE) of the river flows are 60 and 25 Mm^3 per month for the Kelani and Gin Ganga respectively. The differences in total annual outflow between measured and computed estimates from Eq. (2), based on remote sensing data at river basin scale, are 1 and 9% for Kelani and Gin Ganga respectively. The change of $\Delta W_{\mathrm{unsat}}$ on an annual basis for whole Sri Lanka is −33 mm, which fulfills the usual expectation that storage changes on an annual basis can be neglected (see Table 4). The negative sign initially agrees with the below-average annual rainfall. The runoff of 662 mm is equivalent to 38% of the gross inflow and 34% of the net inflow. The net inflow is the gross inflow plus any changes in storage (Molden, 1997). The storage is assumed to be composed of soil moisture change (33 mm) and storage in reservoirs, tanks and aquifers (157 mm).

Table 4
Annual water balance of Sri Lanka between June 1999 and 2000

Flow path	Depth (mm)	Volume (mm^3)
Precipitation	1751	114,734
Evaporation	1279	83,806
Soil moisture Change	−33	−2,165
Rest term	−157	−10,293
Runoff	662	43,386

Somasekaram et al. (1997) used a nationwide average runoff coefficient of 32% based on gauged major river basins. The annual average runoff coefficient is the proportion of the annual rainfall which appears as runoff (Savenije, 1996). Considering the difficulties in properly measuring wild monsoonal rivers and the fact that only a few of the basins are fully gauged, this deviation of 38 versus 32% may be considered acceptable. Since the soil water storage in the unsaturated zone of 1 m depth has decreased by 33 mm, the change in volumetric soil water content is 0.033 $cm^3\ cm^{-3}$. From a soil physical perspective, this can only be achieved if also the groundwater tables have fallen which is part of the rest term (−157 mm). It is very unlikely, that the groundwater decline over the entire island is 1.05 m (−157 mm at a specific yield of 0.15). The estimated maximum drop in groundwater level is 0.25 m, i.e. −37.5 mm on the country scale (−2457 Mm^3). Hence, a part of the total G-term (−10,293 Mm^3) must be attributed to changes in surface water storage as well. Sri Lanka has 18,387 small and large surface water reservoirs (tanks). Taking an average size of 40,000 m^2 per tank (area is 73,458 ha) and a drop in water levels by 1 m yields a surface water storage change of −735 Mm^3. In addition, a 5 m change in the reservoirs of the Mahaweli diversion scheme can contribute about −1250 Mm^3. The remaining part should originate from uncertainties in the water balance and from seawater intrusion, but overall a closure of less than 10% can be regarded as acceptable.

3.2. *Water balance at river basin scale*

Surface inflow originating from outside the river basin may, for a first order approximation of water availability, be tentatively excluded, although it should be recognized that inter-basin transfer through pipelines and irrigation canals is a common phenomenon in Sri Lanka. Aquifers are independent from surface water divides and underground water transfer among basins may occur.

To support water availability analyses, major hydrological parameters for all the 103 river basins in Sri Lanka are given in Appendix A. The runoff coefficients range from 0.08 to 0.67. The Kalu Ganga has an annual discharge of 6366 Mm^3, being the countries maximum runoff volume. The runoff coefficient of the Kalu Ganga is 0.65, also among the highest of Sri Lanka.

The residual of the water balance is not equal in all basins, confirming that basin specific hydrological processes are occurring. These specific processes include the presence of groundwater systems, the diversion of irrigation water etc. The most negative G-term values occur in catchments with a negative surplus, most notably in the northwestern

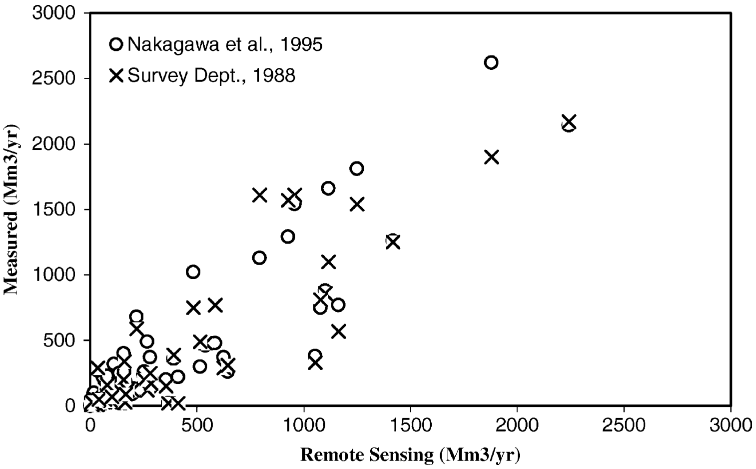

Fig. 5. Comparison of estimated and measured runoff volumes for a majority of basins in Sri Lanka.

province of Mannar. The geological map of Sri Lanka shows this area to contain coastal zone limestone aquifers. The Aruvi Aru river is the basin with the largest rainfall surplus of the northwest, and since it is laying over the coastal aquifers, recharge from the river directly into the aquifer is not unlikely. There are, however, no measurements available to verify this hypothesis. Because of these underground flow connections, the rest term can be as high as −300 to −400 mm per year in some basins (see Appendix A) being one factor greater than the country average of −157 mm per year.

A comparison of the runoff volumes against the values given by Nakagawa et al. (1995) and in the National Atlas of Sri Lanka (Survey Department, 1985) is given in Fig. 5 for all basins with annual discharge under 3000 Mm^3. The values estimated from remote sensing and the measured values shows a very good agreement (correlation coefficients of 97 and 95%, respectively). The regression line fitted through the origin has a slope of 1.29 and 1.33 for the datasets of Nakagawa et al. and Survey Department respectively. This implies that the runoff estimated from remote sensing data for the year 1999–2000 is on average 30% less than the long-term average. A lower than average runoff is feasible given the below-average rainfall received during the study period, but the observed difference cannot explain the 30% difference noted. The month-to-month variability over the 12-month period shows notable deviations (Chandrapala and Wimalasuriya, 2003). Other reasons for underestimating the flow at the river mouth is that more carry-over water is present leaving more rainfall water flowing to the downstream end of the basin, there is simply more rain or that the evaporation is lower than predicted from SEBAL. As SEBAL already underestimates the monthly evaporation over the landscape of Horana by 8%, it is not likely to further decrease the evaporation estimates. If the forests have more cloud cover than observed at the nearest meteorological station (80 km distant), evaporation will be less than estimated and the surplus will be larger. But, the vegetation index is high throughout the year, which suggests that the forest is vigorous and biologically active.

Fig. 5 demonstrates that certain basins display greater deviation than others. The absolute deviation in annual runoff between remotely sensed data and the long-term

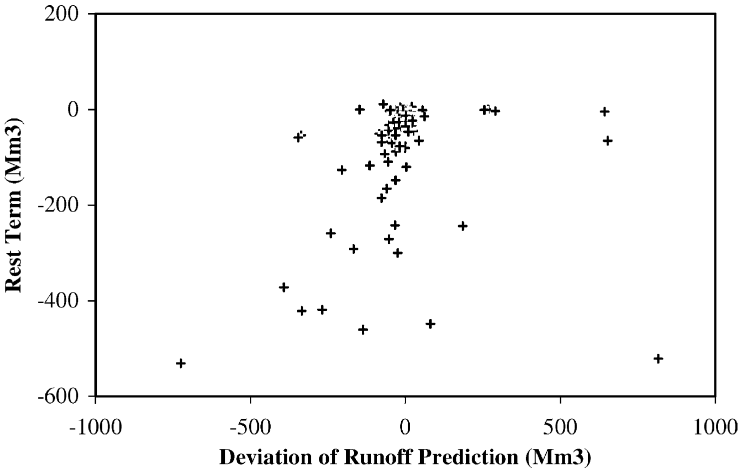

Fig. 6. Deviation of the runoff prediction as a function of the rest term of the water balance.

average is plotted against the *G*-term to investigate the hypothesis that remote sensing and GIS interpreted rainfall data has a systematic bias. If the latter holds true, a systematic error in the prediction of the runoff should be found.

Fig. 6 demonstrates systematic bias is not present. The runoff coefficient (river outflow/ rainfall) has been computed for comparative analyses. Available runoff coefficients, estimated from the work of Perera (in Somasekaram et al., 1997), are given with the values estimated in the present study (see Table 5). The close agreement in the average values (0.40 versus 0.42), reveals that the simplified remote sensing estimation method of annual river runoff is workable. The difference is sometimes greater, which suggests additional research needs to be done.

Accepting the modeled hydrographs of Fig. 4 are reasonable estimates (mean RMSE 43 Mm^3 per month), the accumulated outflow of two basins was within 5% of the remote sensing estimates, we can assume the runoff coefficients (Table 5) are adequate and that the

Table 5
Runoff coefficient of selected river basins

River basin	Perera (1997)	Present study
Mahaweli Ganga	0.33	0.36
Gal Oya	0.35	0.43
Walawe Ganga	0.21	0.44
Kalu Ganga	0.77	0.65
Kelani Ganga	0.62	0.60
Maha Oya	0.42	0.34
Deduru Oya	0.34	0.23
Aruvi Aru	0.12	0.29
Average	0.40	0.42

SEBAL based actual evaporation rates have an error of 8% on monthly basis, and therefore the water balance is sufficiently understood to base water policy analyses upon.

4. Water accounting

It is estimated that the primary water supply worldwide may need to increase by 22% to meet the needs of all sectors by 2025 (Anonymous, 2000b). This implies that additional water resources have to be developed which requires revaluation of river outflow conditions in many cases. These estimates assume that the productivity of water will increase due to better management and strategic river basin planning. Options for increasing water productivity include recycling of water in the basin, improving the reliability of supply, saving water by better tuning water supply with water demand etc. If this does not occur, a 34% increase in water would be required worldwide for agriculture (Anonymous, 2000b). If the unsustainable overdraft of groundwater resources is not arrested—which is a necessity—the increase in primary water supply required doubles to 68%. This implies that critical evaluations are necessary based on water accounting that can show whether water productivity can be improved and whether there is uncommitted outflow left in the basin for developing more diversions.

The terminology of Molden and Sakthivadivel (1999) has been used to evaluate the water use situation across Sri Lanka. The water accounting framework was developed to clarify hydrological conditions and for comparison of the conditions in different basins and countries. The water balance calculations above provide the basic input data. Only results at national scale are presented, although the analysis can be made for individual river basin.

In the water accounting framework water that is depleted by intended uses is considered as ‘process depletion’, an artificially created consumption. This includes the irrigated paddy lands, but also tea, rubber and coconut estates, which are deliberately planted in certain climatic regimes for economic profit. Use of water resources by homesteads and rangelands is considered as a “non-process depletion”, as the management does not directly deliver water for these uses. But the evaporative depletion by homesteads is beneficial for the owners. The natural heritages are the wildlife reserves (national parks, reserves and sanctuaries), wetlands, monsoon forests and other types of forests, approximately 23% of the net inflow is consumed by these heritage and is no longer available for other uses. Due to the protective character of these environments, this should not change in the future (Table 6). Since 23% is committed to mother nature and 34% flows out as uncommitted water, 43% of net available water can be used by other uses. Most of these resources are consumed by homesteads and rangelands (28%). This leaves 15% of the net inflow available for agriculture, irrigated agriculture (7%) and rain-fed agriculture (8%). This practically implies that water resources can be made more productive if rangelands are converted into rain-fed or irrigated agriculture. As the evaporation rates throughout the year of rangelands and rain-fed agricultural areas are similar, replacing rangeland by rain-fed agriculture will hardly affect the month-to-month water balance, and not deprive downstream riparians. Basins with a high runoff coefficient and huge volumes of water unallocated at the estuary are the best candidates for these land use changes.

Table 6
Nation wide water accounts for Sri Lanka during June 1999–2000

Category	Expression	Inflow (mm^3)	Depletion (Mm^3)	Outflow (Mm^3)
Precipitation	Gross inflow	114,734	–	–
Storage change	–	12,458		
Precipitation	Net inflow	127,192 (100%)		
Natural heritages	Committed outflow	–	28,652 (23%)	–
Homesteads	Beneficial non-process depletion	–	8,859 (7%)	–
Rangelands	Non-beneficial non-process depletion	–	26,503 (21%)	–
Irrigated agriculture	Process depletion	–	9,581 (7%)	–
Rain-fed agriculture	Process depletion		10,211 (8%)	
River outflow	Uncommitted outflow	–	–	43,386 (34%)

To help Sri Lanka become self-sufficient in rice, irrigation settlement projects have been implemented. Paddy consumes an amount of water (1226 mm per year) similar to mixed vegetation (1245 mm per year). This fact implies that water availability to other ecosystems cannot change dramatically, if mixed vegetation is converted into irrigated land. The impact on surrounding environments is more on changing the water availability throughout the year. Temporal variability of water availability is however a very important aspect in water scarcity studies, hence caution is required (Amerasinghe et al., 1999).

The total water volume used by paddy fields is 9581 Mm^3. In water accounting terms, this implies that 7% of the net inflow is consumed by the irrigation sector. The total runoff is 43,386 Mm^3 and this is often regarded as water available for use (uncommitted outflow). Hence, an amount of 22% $((9581/43,386) \times 100)$ of 'available water resources' is used by the irrigation sector in Sri Lanka. These two numbers for irrigation use are both far less than the 70–90% often quoted in global water debates. This example shows that global water figures should go together with proper definitions, and with standardization of the data collection. Whereas some studies express irrigation water use as a fraction of all water consumed by man, others refer to a fraction of the runoff or the gross rainfall. The water accounting framework such as presented in Table 6, can prevent these unnecessary confusions.

NOAA-AVHRR data are available worldwide on a daily basis, and can be used together with similar new sensors to map spatially distributed water balances. The data can be found on the world wide web the day following image acquisition. This is an exciting new path to standardize basic water resources data across the globe.

5. Summary and conclusions

The water balance of Sri Lanka was assessed by the spatial distribution of rainfall derived from a network of rain gauge stations and estimates of actual evaporation based on public domain NOAA-AVHRR satellite data. The runoff was assessed from the residual water balance applicable to closed or semi-closed river basins. In certain cases, a rest term was deemed necessary to conserve water. This remainder term expresses the uncertainty of the water balance (<10%) and can be partially explained by changes in storage due to carry-over of water from month-to-month. This is a simple but novel approach to assess uncommitted river outflow and renewable water resources in data sparse environments. The difference between measured and estimated annual river outflow data is 5% with a root mean square error on a monthly basis of 25–60 Mm^3. The error of actual evaporation is 17% on 10-day basis and 1% on a monthly basis.

Knowledge of the island's water balance and its distributions in spatial and temporal domains forms a unique basis for linking land and to water use. The evaporative depletion of all land use types is assessed. Such a dataset makes it feasible to evaluate the consumptive water use of agricultural and forested land, jungle, wetlands and swampy types of vegetation zones. The largest water users per unit area are dry monsoon forests (1407 mm per year), riverine dry forest (1348 mm per year) and rubber plantations (1341 mm per year). The irrigation sector uses not more than 7% of the net inflow (gross rainfall corrected for unsaturated zone water storage). The total agricultural water use is 19,792 Mm^3 and the environmental systems use 64,014 Mm^3, being 15 and 49%, respectively of the net inflow. Agriculture consumes less water than forest and other semi-natural environments in Sri Lanka. These figures are averages and variability within classes is significant.

The water accounts help in classifying water use as process and non-process depletion. This is key information for assessing the opportunities for increasing the productivity of water in basins. At national level, it appears that: (i) low productivity rangeland could be converted into rain-fed agriculture without a significant change in the water balance; and (ii) there is sufficient uncommitted outflow, which can be partially diverted to irrigation to enhance national food security.

The conversion of 10-day rainfall surplus to river flows is associated with uncertainty related to: (i) the accuracy of evaporation mapping in relation to cloudiness; (ii) time integration of the hydrological processes contributing to baseflow; (iii) carry-over water; and (iv) transfer of water across the basin boundaries including underground water intrusion. The applicability of surplus maps based on remote sensing and GIS to Sri Lankan conditions into river flow estimates requires further hydrological research and multiple year datasets.

Acknowledgements

The authors are indebted to Prof. M. Sivapalan of the University of Western Australia for his warm interest in this hydrological research work of river basins in Sri Lanka. His constructive comments have brought the work into a better hydrological perspective. Dr. C. Perry helped to emphasize the need to standardize the description of water flows to multiple users in river basins. Dr. J. Rockstrom from IHE has given input on an earlier manuscript. This study was part of a program funded by the Netherlands Remote Sensing Board (BCRS) through the International Institute for Aerospace Survey and Earth Sciences (ITC), Enschede, The Netherlands

Appendix A. River basin hydrological data for the period June 1999–2000

Number	Basin name	Area (A, km^2)	Rainfall (P, mm)	Evaporation (mm)	Soil moisture change (mm)	Rest term (G, mm)	Runoff depth (mm)	Runoff volume (Mm^3)	Runoff coefficient (R/P)
1	Kelani Ganga	2,292	3087	1310	−64	0	1842	4221	0.60
2	Bolgoda Ganga	378	2552	1319	−48	1	1279	484	0.50
3	Kalu Ganga	2,719	3591	1315	−51	−14	2341	6366	0.65
4	Bentara Ganga	629	3271	1348	−60	−5	1988	1250	0.61
5	Madu Ganga	60	2912	1396	−49	−21	1587	95	0.54
6	Madampe Lake	91	3011	1395	−66	−18	1701	155	0.56
7	Telwatte Ganga	52	2832	1402	−51	−50	1532	80	0.54
8	Ratgama Lake	10	2691	1422	18	−14	1266	13	0.47
9	Gin Ganga	932	3285	1333	−71	6	2017	1880	0.61
10	Koggala Lake	65	2712	1394	−49	−2	1369	89	0.50
11	Polwatte Ganga	236	2478	1388	−45	−1	1135	268	0.46
12	Nilwala Ganga	971	2496	1387	−46	5	1150	1117	0.46
13	Sinimodara Oya	39	1534	1497	−31	−245	314	12	0.20
14	Kirama Oya	225	1738	1431	−44	−145	496	112	0.29
15	Rekawa Oya	76	1217	1378	−42	−349	231	18	0.19
16	Urubokka Oya	352	1538	1337	−59	−185	444	156	0.29
17	Kachchigala	223	1167	1283	−41	−345	270	60	0.23
18	Walawe Ganga	2,471	2077	1170	−5	4	907	2242	0.44
19	Karagan Oya	58	938	1198	−84	−300	124	7	0.13
20	Malala Oya	404	1253	1142	3	−231	339	137	0.27
21	Embilikala Oya	60	935	1208	−8	−444	180	11	0.19
22	Kirindi Oya	1,178	1485	1138	29	−141	459	541	0.31

23	Bambawe Ra	80	1062	1185	5	−268	140	11	0.13
24	Mahasiliwa Oya	13	1001	1341	−27	−418	106	1	0.11
25	Butawa Oya	39	1013	1326	−14	−385	86	3	0.08
26	Menik Ganga	1,287	1417	1226	25	−233	401	515	0.28
27	Katupila Ara	87	1051	1293	−6	−381	145	13	0.14
28	Kurundu Ara	132	1163	1338	−21	−342	188	25	0.16
29	Nabadagas Ara	109	1198	1337	−23	−305	189	21	0.16
30	Karambe Ara	47	1200	1387	5	−351	159	7	0.13
31	Kumbukkan Oya	1,233	1567	1265	26	−198	475	585	0.30
32	Bagura Oya	93	1412	1385	−30	−319	376	35	0.27
33	Girikula Oya	16	1416	1354	−41	−239	342	5	0.24
34	Helawa Ara	52	1478	1357	−35	−249	405	21	0.27
35	Wila Oya	490	1569	1256	−21	−179	512	251	0.33
36	Heda Oya	611	1678	1197	−28	−132	640	391	0.38
37	Karanda Oya	427	1658	1271	−49	−157	593	253	0.36
38	Semana Aru	52	1627	1249	−56	−168	601	31	0.37
39	Tandiadi Aru	22	1617	1022	20	−85	660	15	0.41
40	Kangikadichu Aru	57	1627	1244	−55	−170	609	35	0.37
41	Rufus Kulam	35	1616	1016	−57	−56	713	25	0.44
42	Pannel Oya	106	1633	1180	−57	−141	652	69	0.40
43	Ambalam Oya	117	1590	1067	−66	−87	675	79	0.42
44	Gal Oya	1,813	1805	1215	−31	−161	782	1417	0.43
45	Andella Oya	528	2212	1151	−22	−103	1186	626	0.54
46	Tumpan Keni	9	2364	891	−69	−21	1563	14	0.66
47	Namakada Ara	12	2311	916	−119	−25	1539	18	0.67
48	Mandipattu Aru	101	2276	974	−63	−31	1395	141	0.61
49	Pathantoppu Aru	101	2221	949	−80	−14	1367	138	0.62
50	Vett Aru	26	2130	875	−65	−35	1355	35	0.64
51	Unnichchai	350	2045	1176	−9	−167	1045	366	0.51
52	Mundeni Aru	1,295	1789	1140	−1	−200	850	1101	0.47

Appendix A. (*Continued*)

Number	Basin name	Area (A, km^2)	Rainfall (P, mm)	Evaporation (mm)	Soil moisture change (mm)	Rest term (G, mm)	Runoff depth (mm)	Runoff volume (Mm^3)	Runoff coefficient (R/P)
53	Miyangolla Ela	228	1760	1082	1	−223	899	205	0.51
54	Maduru Oya	1,559	1573	1156	−5	−269	692	1079	0.44
55	Puliyanpota Aru	53	1727	1144	79	−264	767	41	0.44
56	Kirimechchi Odai	78	1676	1195	35	−261	707	55	0.42
57	Bodigolla Aru	166	1616	1236	−10	−258	648	108	0.40
58	Mandan Aru	13	1667	1296	−56	−237	664	9	0.40
59	Makarachchi Aru	38	1679	1248	−7	−234	671	26	0.40
60	Mahaweli Ganga	10,448	1763	1226	−35	−70	641	6697	0.36
61	Kantalai Aru	451	1820	1334	−21	−280	787	355	0.43
62	Palampotta Aru	70	1897	1439	−17	−252	726	51	0.38
63	Panna Oya	145	1869	1302	18	−225	775	112	0.41
64	Pankulam Aru	381	1857	1439	−21	−308	748	285	0.40
65	Kunchikumban Aru	207	1836	1393	13	−332	761	158	0.41
66	Palakutta Aru	21	1814	1253	−45	−204	810	17	0.45
67	Yan Oya	1,538	1629	1296	−7	−345	686	1054	0.42
68	Mee Oya	91	1727	1262	2	−300	762	69	0.44
69	Ma Oya	1,036	1583	1393	−26	−407	622	645	0.39
70	Churiyan Aru	75	1607	1319	−37	−311	636	48	0.40
71	Chavar Aru	31	1634	1428	−37	−361	604	19	0.37
72	Palladi Aru	62	1586	1479	−49	−438	595	37	0.38
73	Manal Aru	189	1536	1370	−59	−373	597	113	0.39
74	Kodalikallu Aru	75	1550	1338	−33	−388	633	48	0.41
75	Per Aru	378	1436	1447	−42	−491	521	197	0.36

77	Maruthapillay Aru	41	1434	1354	−18	−431	530	22	0.37
78	Theravil Aru	91	1401	1370	−73	−407	512	47	0.37
79	Piramenthal Aru	83	1380	1284	−68	−308	472	39	0.34
80	Methali Aru	122	1335	1250	−101	−322	509	62	0.38
81	Kanakarayan Aru	906	1299	1300	−46	−410	455	412	0.35
82	Kalwalappu Aru	57	1319	1143	111	−471	537	31	0.41
82	Akkarayan Aru	194	1240	1031	−46	−232	488	95	0.39
83	Mandakal Aru	300	1206	1237	−119	−365	454	136	0.38
84	Pallavarayan Kaddu	161	1178	1334	−106	−477	427	69	0.36
85	Pali Aru	456	1088	1398	−93	−532	315	143	0.29
86	Chappi Aru	67	1110	1417	−75	−527	296	20	0.27
87	Parangi Aru	842	957	1353	−44	−547	194	164	0.20
88	Nay Aru	567	1171	1388	−44	−479	305	173	0.26
89	Aruvi Aru	3,284	1223	1290	−45	−376	354	1164	0.29
90	Kal Aru	212	973	1432	−67	−568	176	37	0.18
91	Moderagam Aru	943	960	1453	−102	−476	84	80	0.09
92	Kala Oya	2,805	987	1361	−46	−406	77	217	0.08
93	Moongil Aru	44	1172	1325	−59	−300	206	9	0.18
94	Mi Oya	1,533	995	1403	34	−546	104	159	0.10
95	Madurankuli Aru	73	1034	1322	−77	−316	104	8	0.10
96	Kalagamuna Oya	153	1125	1202	−39	−304	266	41	0.24
98	Rathambala Oya	218	1436	1298	−81	−247	466	102	0.32
99	Deduru Oya	2,647	1311	1308	−99	−197	300	794	0.23
100	Karambala Oya	596	1461	1331	−95	−248	473	282	0.32
101	Ratmal Oya	218	1838	1392	−68	−249	763	166	0.42
102	Maha Oya	1,528	1859	1361	−86	−43	627	958	0.34
103	Attanagalla Oya	736	2595	1385	−44	−6	1260	927	0.49

References

Amerasinghe, U., Mutuwatta, L., Sakthivadivel, R., 1999. Water scarcity variations within a country: a case study of Sri Lanka. Research Report 32, International Water Management Institute (IWMI), Colombo, Sri Lanka, pp. 29.

Anonymous, 2000a. Dialogue on water for food and environmental security, summary report planning and design meeting. International Water Management Institute (IWMI), Colombo, Sri Lanka, pp. 16.

Anonymous, 2000b. Water issues for 2025, a research perspective. International Water Management Institute to the World Water Vision for Food and Rural Development, pp. 26.

Bastiaanssen, W.G.M., Pelgrum, H., Wang, J., Ma, Y., Moreno, J.F., Roebeling, R.A., van der Wal, T., 1998. The Surface Energy Balance Algorithm for Land (SEBAL). Part 2. Validation. J. Hydrol. 212–213, 213–229.

Bastiaanssen, W.G.M., Molden, D.J., Makin, I.W., 2000. Remote sensing for irrigated agriculture: examples from research and possible applications. Agric. Water Manage. 46, 137–155.

Bouwer, H., 2000. Integrated water management: emerging issues and challenges. Agric. Water Manage. 45, 217–228.

De Bruin, H.A.R., van den Hurk, B.J.J.M., Kohsiek, W., 1995. The scintillation method tested over a dry vineyard area. Bound. Layer Meteorol. 76, 25–40.

Chandrapala, L., Wimalasuriya, M., 2003. Satellite measurements supplemented with meteorological data to operationally estimate actual evaporation of Sri Lanka, Agric. Water Manage. 58, 89–107.

Choudhury, B.J., 1997. Estimating areal evaporation using multispectral satellite observations. In: Sorooshian, et al. (Eds.), Land Surface Processes in Hydrology NATO-ASI Series, vol. 146, Springer, Berlin, pp. 347–381.

Hemakumara, M., Chandrapala, L., Moene, A.F., 2003. Evapotranspiration fluxes over mixed vegetation areas measured from large aperture scintillometer. Agric. Water Manage. 88, 109–122.

Kite, G., Droogers, P., 2000. Comparing evapotranspiration estimates from satellites, hydrological models and field data. J. Hydrol. (229), 3–18.

Molden, D.J., 1997. Accounting for water use and productivity, SWIM Paper 1, system-wide initiative for water management. International Water Management Institute, Colombo, Sri Lanka, p. 16.

Molden, D.J., Sakthivadivel, R., 1999. Water accounting to assess uses and productivity of water. Int. J. Water Resour. Dev. 155 (1–2), 55–71.

Muthuwatta, L., Chemin, Y., 2003. Vegetation growth zonation of Sri Lanka for improved water resources planning. Agric. Water Manage. 58, 123–143.

Nakagawa, K., Edagawa, H., Nandakumar, V., Aoki, M., 1995. Long-term Hydrometeorological Data in Sri Lanka: Data Book of Hydrological Cycles in Humid Tropical Ecosystems, Part I. University of Tsukuba, Japan.

Perry, C.J., 1998. The IWMI water resources paradigm—definitions and implications. Agric. Water Manage. 40, 45–50.

Renault, D., Hemakumara, M., Molden, D.J., 2001. Importance of water consumption by perennial vegetation in irrigated areas of the humid tropics: evidence from Sri Lanka. Agric. Water Manage. 46, 215–230.

Savenije, H.H.H., 1996. The runoff coefficient as the key to moisture recycling. J. Hydrol. 176, 219–225.

Seckler, D., Amarasinghe, U., Molden, D.J., De Silva, R., Barker, R., 1998. World water demand and supply, 1990–2025: scenarios and issues. Research Report 19, International Irrigation Management Institute, IIMI, Colombo, Sri Lanka, p.40.

Schaake, J.C., Koran, V.I., Duan, Q.Y., Mitchell, K., Chen, F., 1996. Simple water balance model for estimating runoff at different spatial and temporal scales. J. Geophys. Res. 101, 7461–7475.

Somasekaram, T., Perera, M.P., De Silva, M.B.G., Godellawatta, H., 1997. Arjuna's Atlas of Sri Lanka. Arjuna Consulting Co. Ltd., Dehiwala, Sri Lanka, p. 220.

Survey Department, 1985. The National Atlas of Sri Lanka. Survey Department of Sri Lanka, Colombo, Sri Lanka.

Wang, J., Ma, Y., Menenti, M., Bastiaanssen, W.G.M., Mitsuta, Y., 1995. The scaling-up of processes in the heterogeneous landscape of HEIFE with the aid of satellite remote sensing. J. Meteorol. Soc. Jpn. 73, 1235–1244.