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Water accounting for conjunctive groundwater/surface water management: case of the Singkarak–Ombilin River basin, Indonesia

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Abstract

Because water shortages limit development in many parts of the world, a systematic approach is needed to use water more productively. To address this need, Molden and Sakthivadivel [Water Resour. Dev. 15 (1999) 55-71] developed a water-accounting procedure for analyzing water use patterns and tradeoffs between users. Their procedure treats groundwater and surface water as a single domain. We adapted this procedure to account for groundwater and surface water components separately, and applied the adapted procedure to the Singkarak–Ombilin River basin, Indonesia, where groundwater is a significant part of the overall water balance. Since 1998, a substantial proportion of water has been withdrawn from Singkarak Lake and diverted out of the basin, resulting in significant impacts on downstream water users and the lake ecosystem. Based on 15–20 years (1980–1999) of hydrometeorological, land use, soil, and other relevant data, a simple groundwater balance model was developed to generate the hydrogeologic information needed for the water-accounting procedure. The water-accounting procedure was then used to evaluate present and potential future water use performance in the basin. By considering groundwater and surface water components separately, a more realistic estimate of water availability was calculated than could be obtained by lumping these components together. Results show that the diversion of 37 m^3/s from Singkarak Lake increases the amount of water that is not available for other uses, such as for irrigation, from 57–81 to 81–95% of total water available in the basin. The new water accounting procedure also demonstrates the viability of increasing downstream water supply and water use performance during the dry months (June–September). For example, by increasing irrigation during the wet months (January–April) or tapping water from a shallow, unconfined aquifer during the dry months, while keep maintaining sustainable groundwater levels.

Keywords: Water accounting; Water balance; Recharge; Baseflow; Vadose zone; Water depletion

1. Introduction

Water is becoming the limiting factor for development in many parts of the world. A systematic approach is needed to communicate how water is

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being used and how water resource developments will affect present use patterns. A water-accounting procedure was introduced by Molden (1997) and developed by Molden and Sakthivadivel (1999) to address this need. The Molden and Sakthivadivel (M–S) procedure provides terminology and measures to describe the use and productivity of water resources. It has proven useful to identify means for improving water management and productivity while maintaining environmental integrity, and is now being applied in The Philippines, Nepal, Pakistan, India, Sri Lanka, and China (IWMI, 1999; Molden et al., 2001; Renault et al., 2001).

The M–S water-accounting procedure is based on a water balance approach that combines groundwater and surface water as a single domain. However, in many cases, optimal water resource management and conservation require that groundwater be distinguished from surface water. This is especially true where groundwater plays a significant role in the overall water balance, such as in central and northern China, northwest and southern India, parts of Pakistan, and much of the North Africa, Middle East, and the glacial aquifers in the plains region of the United States (Postel, 1999). For these cases, the original M–S approach could potentially prove quite useful, but needs further development to separate groundwater from surface water.

In much of the world, surface water and rainfall have traditionally supplied all water demands. But as those demands increase, other sources are sought. A viable option in many basins is groundwater. However, if groundwater has not previously been exploited, it is unlikely that local storage and flow mechanisms are well understood. In these cases, appropriate hydrogeologic data are unavailable for water-accounting analysis, and must first be synthesized from other hydrologic data before water accounting can be applied. Consequently, a simple method to estimate such hydrogeologic data with minimal hydrologic inputs, such as the Thornthwaite–Mather (T–M) water balance model (Thornthwaite and Mather, 1955, 1957), is pivotal in the overall water accounting procedure.

The Singkarak–Ombilin River basin in West Sumatra Province, Indonesia, is a case in point. This basin consists of two major sub-basins, the Singkarak sub-basin in the upstream (western part) and the Ombilin River basin in the downstream (eastern part) (Fig. 1). All flows from the Singkarak sub-basin drain into Singkarak Lake (106 km^2, 365 m.a.s.l.), the largest lake in the basin (Fig. 1). There are two major rivers flowing into the lake, the Sumpur River from the northwest and the Sumani/Lembang River from the southeast in which water supply for the latter was largely determined by the supply from Dibawah Lake (106 km^2, 1400 m.a.s.l.) (Fig. 1). The only outlet from Singkarak Lake is the Ombilin River, which flows eastward to the Inderagiri River in the plains of Rian Province. Until recently, sufficient surface and rainwater were available to meet all water needs within the basin. However, demands for surface water diversions to the Singkarak Hydroelectric Power Plant (HEPP), which began operation in May 1998, have stressed the available supply to the extent that the largest lake in the basin has begun to recede, and have caused significant outflow reduction to the Ombilin River (downstream). Conflicts between the management of the HEPP and other water users have ensued downstream of the lake. Development of additional available water sources could potentially supply some of the increased demands. Although a shallow aquifer underlies the basin, it has never been exploited and little is known about its capacity to help meet the increasing water demands. Yet its potential to store water during wet periods for later use could prove pivotal in circumventing water shortages. As a precursor to planning and implementing mitigative water management strategies, the potential for groundwater to increase overall water availability in the basin needs to be quantified.

The objectives of this study were to: (1) modify the M–S water-accounting procedure to account for groundwater separately; (2) use a modified Thornthwaite–Mather water balance model to generate groundwater data for the modified water-accounting procedure; (3) apply the modified water-accounting procedure to evaluate past water use (1985–1998) and provide opportunities for improving future water management of the Singkarak–Ombilin River basin, emphasizing the potential role of groundwater in augmenting current water supplies in the downstream.

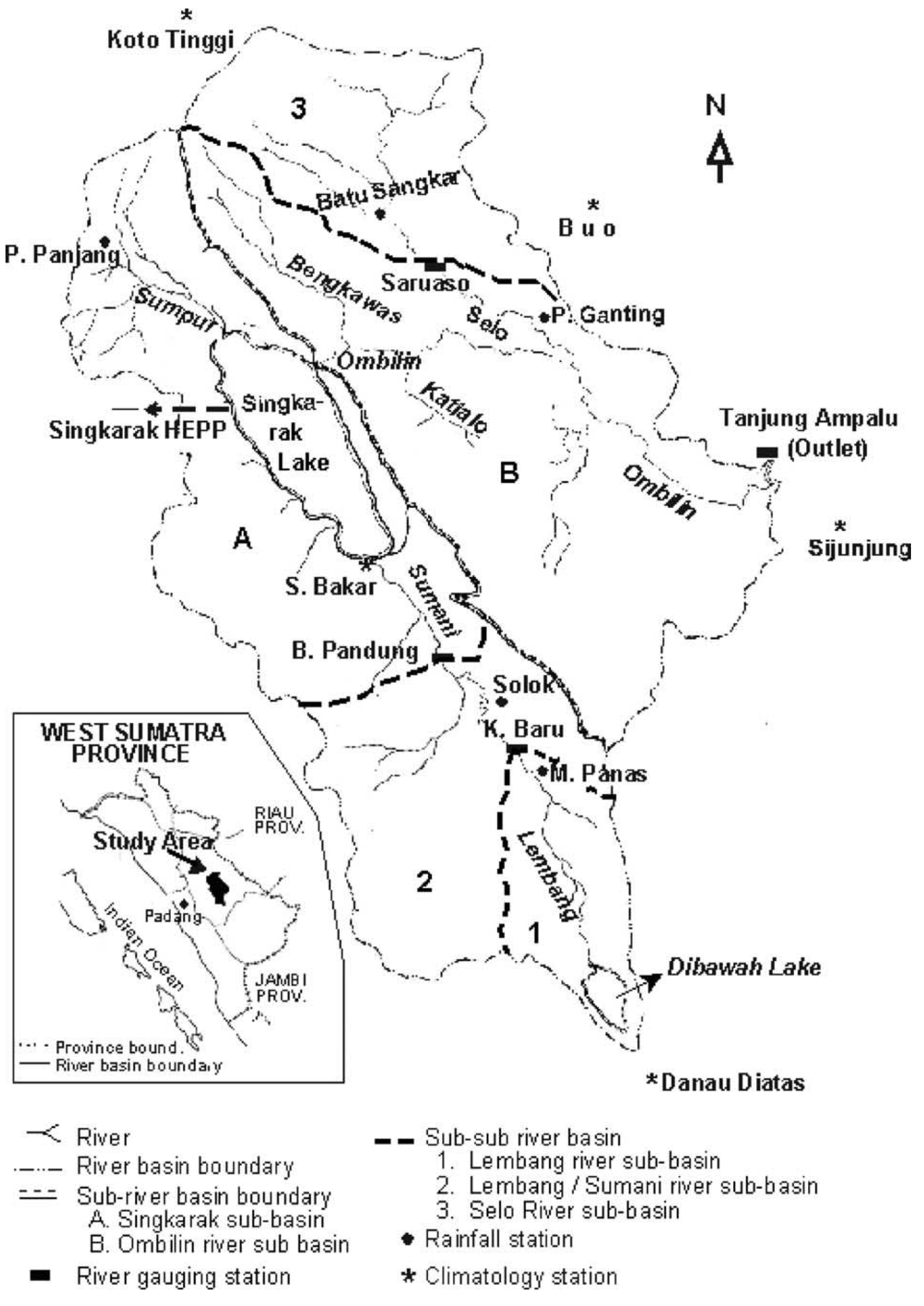

Fig. 1. The Singkarak–Ombilin River Basin.

2. Study area

The 2210 km^2 Singkarak–Ombilin River basin (Fig. 1) located in the West Sumatra Province, Indonesia, is a hilly, dendritic drainage basin located at latitude 00°00′30″–01°02′40″S, longitude 100°22′45″–100°51′00″E, and altitude 240–2760 m.a.s.l.

The Singkarak sub-basin (1096 km^2) in the upstream is primarily mountainous and hilly, while the Ombilin River sub-basin (1114 km^2) in the downstream is a relatively flat, undulating plateau (Center for Soil and Agroclimate Research Agency, 1990). Geologically, the Singkarak sub-basin consists of Quaternary-age volcanoes and the Ombilin River sub-basin consists of Tertiary-age volcanoes. The soil in the basin is deep, porous, and highly permeable (soil permeability is 10–75 cm/h) (Saidi, 1995), with the top 30 cm typically characterized as silty clay loam, silty clay, and clay (Saidi, 1995; Imbang et al., 1996). Land use is largely agricultural (Table 1). The villages are considered to be 85 and 15% rural and urban, respectively. Farm households compose around 70% of the total households. As a major cultural center of eastern West Sumatra, the area around Solok is the most rapidly growing part of the basin (229 and 283 inhabitants/km^2 in 1985 and 1998, respectively).

The humid, tropical climate is characterized by high temperature throughout the year and heavy rainfall (Scholz, 1983). Based on 1980–1999 data published by local and national Meteorological and Geophysical Agencies, average annual precipitation ranges from 1.7 to 2.9 m, with peaks at the end and beginning of each year (Fig. 2). Mean monthly rainy days range from 5 to 24 days, while mean annual pan evaporation and temperature range from 3.9 to 5.3 mm/day and 22.5 to 26.2 °C, respectively.

A shallow, unconfined aquifer underlies the majority of the basin. The water table ranges from about 0.3–15 m below the land surface (Sudadi, 1983; Arief and Ruchijat, 1990). The aquifer is locally recharged by infiltrated precipitation. However, although monthly precipitation is the lowest in June, minimum streamflow does not occur until August (Fig. 2). The delayed low flow is caused by baseflow, or groundwater discharge to stream channels from the slowly declining water levels in the aquifer.

Surface water in the Singkarak–Ombilin River basin is used for irrigation, domestic activities, commercial and home industrial uses, the Singkarak HEPP, fish culture, livestock, and recreation. In the downstream (Ombilin River sub-basin) water is also consumed for coal washing and electricity generation by thermal power plants. Pumps and waterwheels are used for irrigation in the downstream while pumps and gravity are used in the upstream. Since beginning operation in May 1998, the Singkarak HEPP has diverted a substantial proportion of water from Singkarak Lake to outside the basin, the west coast of Sumatra, which receives a high amount of rainfall. The diversion reduced discharge to the Ombilin River (east coast of Sumatra), which receives a lesser amount of rainfall than the west coast, from an average discharge of 53 to 2–6 m^3/s. The reduced flow has seriously affected the lake level and downstream water users, leading to water use conflicts.

Table 1
Land use changes

Land use	Singkarak (%)	Ombilin (%)	Total (%)
Irrigated rice field			
1985	14.1	5.8	10.0
1998	12.9	4.4	8.7
Change	−1.2	−1.4	−1.3
Rainfed rice field			
1985	2.5	7.4	5.1
1998	1.6	7.0	4.4
Change	−0.9	−0.4	−0.7
Other field crops[a]			
1985	11.7	18.3	15.0
1998	14.7	25.1	19.9
Change	+3	+6.8	+4.9
Plantation[a]			
1985	6.4	10.3	8.4
1998	7.1	12.5	9.8
Change	+0.7	+2.2	+1.4
Forest			
1985	29.7	20.6	25.1
1998	24.9	13.8	19.3
Change	−4.8	−6.8	−5.8
Shrubs/bush			
1985	15.0	19.5	17.3
1998	18.2	19.7	18.9
Change	+3.2	+0.2	+1.6
Water body			
1985	10.6	0	5.3
1998	10.6	0	5.3
Change	0	0	0
Others[b]			
1985	9.9	17.8	13.9
1998	10.1	17.2	13.7
Change	+0.2	−0.6	−0.2

[a] Rainfed.
[b] Fallow, homestead, pasture, open land, fish pond, and natural springs.

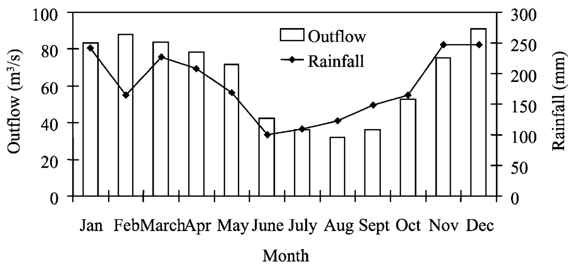

Fig. 2. Mean monthly precipitation and outflows in the Singkarak–Ombilin River basin, 1980–1999. Precipitation data were collected from five rainfall stations and five climatology stations located in the basin (Fig. 1) and outflows were measured at the Tanjung Ampalu river gauging station. Average precipitation depth was calculated based on the Thiessen method.

A survey conducted by the Center for Irrigation, Land and Water Resources, and Development Studies of Andalas University in 2000 found that 50% of the 366 bamboo waterwheels used for irrigation downstream became inoperable after reduced flow rendered the Ombilin River too shallow for their intakes.

Increasing water demands by the hydropower diversion from Singkarak Lake have increased pressure on agricultural water management downstream of the lake. With nearly all surface water fully utilized, groundwater exploitation is an appealing option to meet the increased water demand. The time lag between the lowest precipitation and streamflow (Fig. 2) suggests the presence of a significant aquifer. However, availability and reliability of the groundwater resources are unknown, as are the potential impacts of various conjunctive management approaches.

3. Theory

3.1. The Molden and Sakthivadivel water-accounting procedure

The Molden and Sakthivadivel (M–S) water-accounting procedure has proven useful for helping to understand the tradeoffs needed to improve water use effectiveness in water scarce basins (Molden, 1997; Molden and Sakthivadivel, 1999; Molden et al., 2001; Renault et al., 2001). The M–S procedure applies a simple water balance to a given domain over a given time period. A domain is delineated spatially, both areal (i.e. river basin) and depth (i.e. root zone, vadose zone, groundwater), and bounded in time (i.e. annual water year, particular growing season). The procedure can be applied to three spatial levels: macro (basin or sub-basin), mezzo (service area within a basin, such as a water supply or irrigation service), and micro (i.e. the root zone of an irrigated field, or a particular industrial process). For the Singkarak–Ombilin River basin, our main emphasis is on the basin level. At this level, the M–S water-accounting procedure combines groundwater, soil water, and surface water into a single domain, which extends from the canopy surface to the aquifer bottom with an overall water balance equation of

$$I = D + Q + \Delta S \tag{1}$$

and

$$I = P + S_s + S_g \tag{2}$$

$$D = ETa + V + U \tag{3}$$

$$Q = Q_s + Q_g \tag{4}$$

$$\Delta S = \Delta S_s + \Delta S_{sm} + \Delta S_g \tag{5}$$

where I is the inflow; D, the water depletion; Q, the outflow; ΔS, the storage change; P, the precipitation; S_s and S_g, the surface and sub-surface flow into the basin, respectively; ETa, the actual evapotranspiration from vegetation; V, the evaporation from free water surfaces and open land; U, the domestic and non-domestic depletive uses; Q_s, the surface runoff (including interflow); Q_g, the baseflow; ΔS_s, the change in surface water storage; ΔS_{sm}, the change in soil moisture content; ΔS_g is the change in groundwater storage. The units of all the parameters are expressed as volumetric flow rates (m^3/yr).

The unique feature of the M–S water accounting procedure is its classification of each water balance component into water use categories that reflect the consequences of human interventions in the hydrologic cycle as summarized in Table 2. The most important feature of the procedure is its detailed categorization of water depletion, D, defined as a use or removal of water from a domain of interest that renders the water unavailable, or unsuitable for further

Table 2
Water accounting components of the Singkarak–Ombilin River basin

Water-accounting components	Definition	Water-accounting parameter	
		Singkarak sub-basin (upstream)	Ombilin River sub-basin (downstream)
Surface water accounting			
Inflow (I)			
Gross inflow (I_g)	Total amount of water flowing into the domain	Precipitation	Precipitation, outflow from Singkarak Lake
Net inflow (I_n)	Gross inflow plus any changes in storage[a]	Precipitation, soil moisture change, lake level changes	Precipitation, outflow from Singkarak lake, soil moist. change
Storage change (ΔS)		Soil moisture change Dibawah and Singkarak Lakes level changes	Soil moisture change
Water depletion (D)			
Process depletion (D_p), beneficial	Water depletion that produces human-intended goods	ET from agricultural crops[b] Domestic, non-domestic[c] livestock depletive uses	ET from agricultural crops[b] Domestic, non-domestic[d] livestock depletive uses
Non-process depletion, beneficial (D_{nb})	Water depletion that is used naturally or not for human intended purposes	ET from natural forest	ET from natural forest
Non-process depletion, non-beneficial (D_{nn})	Water depletion results in a low or negative value	ET from free surface, shrubs/ bush, fallow, homesteads[e]	ET from free surface, shrubs/bush, fallow, homesteads[e]
Outflow (Q)			
Committed (Q_c)	Allocated to downstream process or environmental uses within a domain	Downstream commitment (2–6 m^3/s) (as of May 1998)[f]	None
Uncommitted, utilizable (Q_{uu})	Neither depleted nor committed, available for use within the domain, but flows out due to lack of storage or operational measures. Infrastructure exists to retain water in the domain.	Outflow from Singkarak Lake[g]	Surface runoff Groundwater recharge
Uncommitted, non-utilizable (Q_{un})	Same as above, however infrastructure does not exist	None	None
Groundwater accounting[h]			
Inflow (I)			
Gross inflow (I_g)	See the definition above	Groundwater recharge	Groundwater recharge
Net inflow (I_n)	See the definition above	Groundwater recharge, groundwater storage change	Groundwater recharge, groundwater storage change
Storage change (Δ)		Groundwater storage change	Groundwater storage change
Outflow (Q)			
Utilizable uncommitted outflow (Q_u)	See the definition above	Groundwater discharge (baseflow)	Groundwater discharge (baseflow)

[a] If water is removed from storage, then net inflow exceeds gross inflow; conversely, if water is added to storage, then net inflow is less than gross inflow.
[b] Evapotranspiration (ET) from irrigated and non-irrigated crops, plantations, and pasture.
[c] Commercial and industrial depletive uses, including the uses for the Singkarak HEPP and AMIA bottled water industry since May 1998.
[d] Commercial and industrial depletive uses, including the uses for the Ombilin coal-washing plant, Ombilin and Salak thermal power plants.
[e] These uses were considered non-beneficial because of low value when compared to the forest, natural landscape, or agricultural uses.
[f] Used for irrigation, domestic water supply, Ombilin coal-washing plant, Ombilin and Salak thermal power plants.
[g] No uncommitted utlizable outflow after May 1998.
[h] No groundwater depletion. Committed or uncommitted, non-utilizable groundwater discharge was not identified.

use, either within the domain or downstream. According to Keller and Keller (1995) and Seckler (1996), water is depleted by four processes: evaporation, flows to sinks, pollution, and incorporation into a product.

The M–S water-accounting procedure produces physically based water accounting indicators, which will be described in more detail later. By comparing water-accounting indicators, one can easily assess relative water use performance either within a domain or between domains, which is vital for identifying opportunities for improving water management, especially when all water supplies are fully utilized, defining a *closed basin* (Seckler, 1996).

3.2. The modified water-accounting procedure

To rigorously apply the M–S procedure to the Singkarak–Ombilin River basin, where groundwater storage could potentially provide a new source of available water during the dry part of the year, groundwater and surface water clearly must be analyzed as separate entities. Therefore, we modified the M–S procedure by dividing the spatial domain of analysis into above groundwater and groundwater domains. The above groundwater domain extends from the canopy surface to the water table, while the groundwater domain extends from the water table to the aquifer bottom. Consequently, the water balance equation for the entire domain of analysis is divided into separate water balances where the exchange term between the two domains is recharge, R. For the above groundwater domain

$$I^s = P + S_s + \mathrm{Irr}_g \tag{6}$$

$$D^s = ETa + V + U \tag{7}$$

$$Q^s = Q_s + R \tag{8}$$

$$\Delta S^s = \Delta S_s + \Delta S_{sm} \tag{9}$$

and for the groundwater domain

$$I^g = R + S_g \tag{10}$$

$$D^g = \mathrm{Irr}_g \tag{11}$$

$$Q^g = Q_g \tag{12}$$

$$\Delta S^g = \Delta S_g \tag{13}$$

where superscripts s and g represent parameters for the above groundwater and groundwater domains, respectively; Irr_g, the groundwater irrigation [L^3/T], and R is the groundwater recharge [L^3/T].

The modified water-accounting approach is depicted graphically in Fig. 3, which is divided vertically into above groundwater and groundwater domains, and horizontally into the upstream (including Singkarak Lake) and downstream. Excess irrigation water and infiltrated precipitation percolate downward and recharge the shallow, unconfined aquifer. Because some recharge stored in the wet period can potentially be depleted for beneficial purposes later during the drier period, we refer to groundwater recharge as *potential beneficial depletion*. The term *potential* indicates that some of the recharge later discharges as groundwater to rivers, where the discharge may not be depleted beneficially. When irrigation increases during the wet season, recharge to groundwater also increases. This additional recharge leads to additional utilizable outflow during low flow periods, which later can be directly depleted for intended purposes.

To apply this modified accounting procedure, groundwater recharge and baseflow must be quantified explicitly. These data are generally not available and must be calculated. The procedure is detailed in Section 3.3.

3.3. The modified Thornthwaite–Mather water balance model

To estimate groundwater recharge and baseflow we modified the Thornthwaite–Mather (T–M) monthly time step water balance model (Thornthwaite and Mather, 1955, 1957; Steenhuis and van der Molen, 1986) to account for the vadose and saturated zones separately. The modified T–M model calculates monthly groundwater recharge and discharge from monthly climate data in one dimension. In addition, the modified T–M monthly water balance model was used to calculate soil moisture and groundwater storage changes, and inflow to Singkarak Lake, as needed for the water-accounting procedure.

3.3.1. Vadose zone

Most applications of the T–M procedure use a monthly time step. Soil moisture either increases or

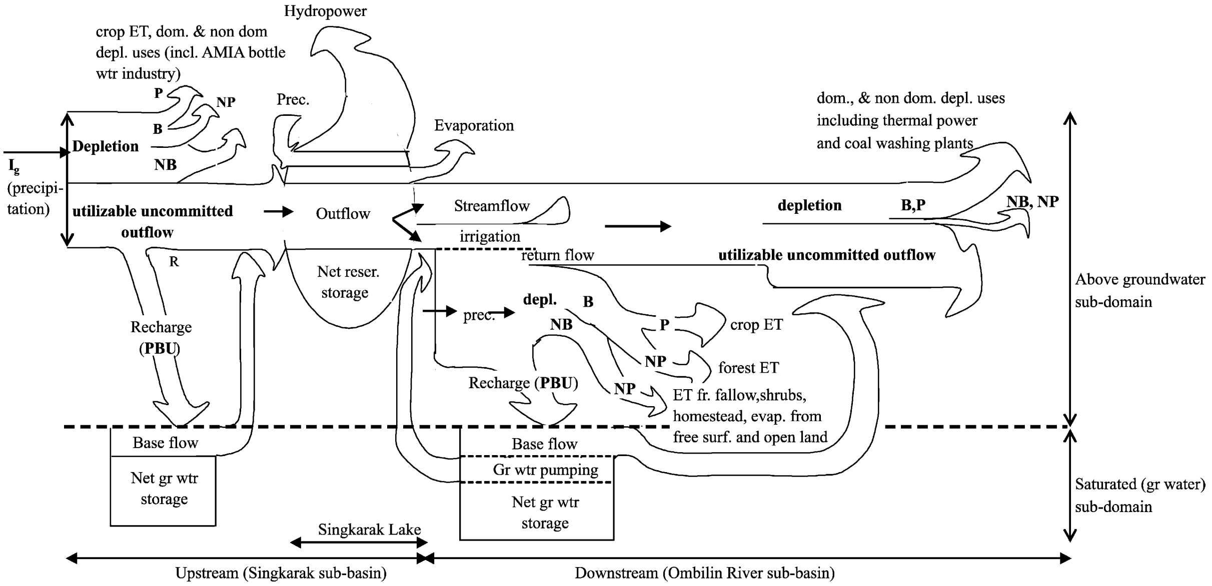

Fig. 3. Modified water accounting of the Singkarak–Ombilin River basin. GI: gross inflow, ET: evapotranspiration, P: process, NP: non-process, U: utilizable, B: beneficial, NB: non-beneficial, PBU: potential beneficial depletion. As of May 1998, outflow from Singkarak Lake is regulated at 2–6 m^3/s.

decreases monthly, depending on whether precipitation, P_t, is greater or less than potential evapotranspiration, ETp_t. When $P_t < ET_{p\ t}$, available water in the root zone is in deficit and no water percolates from the soil profile. Thus

$$Ssm_t = Ssm_{t-1} \exp[-(ETp_t - P_t)/(S_{fc} - S_{wp})] \quad (14)$$

where Ssm_t and Ssm_{t-1} are the available water stored in the root zone at the end of the month (t) and previous month ($t-1$), respectively; and $(S_{fc} - S_{wp})$ is the effective water-holding capacity in the root zone (soil moisture at field capacity, S_{fc}, minus soil moisture at wilting point, S_wp). All units are expressed as length or volume. When $ETp < P_t$, water stored in the root zone increases according to:

$$Ssm_t = \min[Ssm_{t-1} + P_t - ETp_{\ t}), (S_{fc} - S_{wp})] \quad (15)$$

If the resulting $Ssm_t > S_{fc} - S_{wp}$, then deep percolation (recharge), R_t, occurs, where

$$R_t = Ssm_t - (S_{fc} - S_{wp}) \quad (16)$$

Further practical applications of the T–M model to the root zone can be seen in Thornthwaite and Mather (1955, 1957), Dunne and Leopold (1978), Alley (1984) and Steenhuis and van der Molen (1986).

3.3.2. Saturated zone

Surface runoff is negligible in the Singkarak–Ombilin River basin because the soils are highly permeable. Therefore, irrigation water and infiltrated precipitation in excess of the root zone water-holding capacity is assumed to recharge groundwater. In response to recharge, groundwater levels rise. The resulting increase in hydraulic head induces lateral sub-surface flow toward the drain (lake/river). Eventually, this flow becomes groundwater discharge, which is assumed to be the only contributor to baseflow. Assuming a linear baseflow recession curve, aquifer drainage can be expressed as an exponential decay process

$$S_{g\ t} = S_{g\ t-\Delta t} \exp(-\alpha \Delta t) \quad (17)$$

where $S_{g\ t-\Delta t}$ and $S_{g\ t}$ are the groundwater levels (groundwater storage per unit area) above a reference level at the beginning and end of each month, respectively, units are expressed as length [L], and $S_{g\ t-\Delta t}$ equals the sum of the groundwater level at the end of month $t-1$, $S_{g\ t-1}$, and the average groundwater recharge during month t, R_t, weighted by land use; Δt is the number of days in the month; and α is a constant, representing a characteristic storage delay in the basin [L/T]. Factors controlling the delay probably include perennial stream density and length, basin slope, and aquifer hydraulic characteristics. Finally, groundwater discharge, Q_g, is determined as

$$Q_g = A(S_{g\,t} - S_{g\,t-1}) \tag{18}$$

where A is the catchment area in $[L]^2$.

4. Applications

4.1. Application of the modified Thornthwaite–Mather water balance model

4.1.1. Data and methods

The modified T–M model was tested on three river sub-basins of the Singkarak–Ombilin River basin: the Lembang (166 km^2), Lembang/Sumani (515 km^2), and Selo (329 km^2) (Fig. 1). Hydrologic, land use, and soil data for the period 1985–1998 were obtained or synthesized for each sub-basin/basin.

Daily (when available) and monthly precipitation data from five rainfall stations (Padang Panjang, Batu Sangkar, Solok, Muara Panas, and Padang Ganting) (Fig. 1) were obtained from the Provincial Meteorological and Geophysical Agency at Sicincin and the Meteorological and Geophysical Agency Head Office at Jakarta. Additional precipitation records from five climatology stations (Koto Tinggi, Buo, Sijunjung, Saning Bakar, and Danau Diatas) located within and around the basin (Fig. 1) were obtained from the Water Resources and Development Service of West Sumatra. Average daily or monthly precipitation falling into each sub-basin was calculated by the Thiessen method (Linsley et al., 1982; Schwab et al., 1993). Seven percent of the monthly data were missing. Missing monthly data were estimated as the mean of all measured monthly precipitation for that particular station.

Daily maximum, minimum, and average values of temperature, pan evaporation, relative humidity, wind speed, and sunshine duration were obtained from the five climatology stations. Eight percent of the pan evaporation data were missing. Missing mean monthly pan evaporation was estimated by adjusting the mean monthly pan evaporation from the previous year according to the difference in monthly precipitation between years. Unweighted average pan evaporation data from stations located within or around each sub-basin were used for analysis.

Potential evapotranspiration, ET_p, was obtained by multiplying unweighted average class A pan evaporation with a pan coefficient of 0.76. This coefficient was obtained by calibrating the reference evapotranspiration, ET_0, computed with CROPWAT 5.7 (Allen et al., 1998) to pan evaporation. The coefficient closely agrees with Allen et al. (1998), whose values ranged between 0.75 and 0.85 for wind speeds of less than 2 m/s and humidity greater than 70%.

Land use data were obtained from annual reports published by the provincial and local offices of the Food Crops Agricultural Extension Services, Bureau of Statistics, and Plantation Services. The natural forest area was cross-checked with data obtained from the National Coordination Agency for Surveys and Mapping and National Forest Inventory Project (under the Ministry of Forestry and Plantation). Land use changes from 1985 to 1998 period are presented in Table 1.

Lacking local soil- and crop-physical data, effective water-holding capacity in root zones was assumed to be 6 cm for rice (Oldeman et al., 1979; Pramudia et al., 1998), 7.5 cm for 'other field crops' (Mock, 1973; Oldeman et al., 1979), 15 cm for 'bush', 'shrubs', 'fallow', and 'homestead (mostly fallow)' (Mock, 1973), 37.5 cm for forest, and 25 cm for plantation crops (Thornthwaite and Mather, 1957).

Daily streamflow measurements were obtained from the Research Institute for Water Development (under the Ministry of Settlement and Regional Infrastructure) and Water Resources and Development Service of West Sumatra for four automated water level recorder (AWLR) stations: Koto Baru, Bandar Pandung, Saruaso, and Tanjung Ampalu (Fig. 1). These stations are the outlet of the Lembang, Lembang/Sumani, and Selo River sub-basins, and the Singkarak–Ombilin River basin, respectively (Fig. 1).

The constant, α, was determined by plotting $Q_{t-\Delta t}$ versus Q_t (t in day) for available baseflow recessions, as described in Linsley et al. (1982). It should be noted that since the authors present a different form of exponential outflow function, in this case the constant α equals to $-\ln(K_r)$, where K_r is the slope of the lowest envelope of the recession flow data. As the modified T–M model would be tested to three sub-basins (the Lembang, Lembang/Sumani, and Selo sub-basins), K_r was derived for these three sub-basins. Fig. 4 shows how K_r was obtained for the Lembang River sub-basin based on daily recession flow data from the Koto Baru gauging station for 1992–1998. The resulting values of α are 0.018, 0.008, and 0.015, for the Lembang, Lembang/Sumani, and Selo sub-basins, respectively. The straight line of the slope K_r demonstrates that the baseflow recession curve of this basin was linear ($dQ/dt = -\alpha Q$), where α is constant and equal to $-\ln[K_r]$ and, therefore, Eq. (17) is valid (Zecharias and Brutsaert, 1988; Brutsaert and Lopez, 1998).

4.1.2. Results

The modified T–M model was run for a monthly time step from January 1985 to December 1998 and was initiated by specifying the starting amount of water stored in the root zone (Ssm_0) of each crop/vegetation, which was assumed to be equal with its effective water-holding capacity. The assumption was based on the fact that the average precipitation peaks at the end and beginning of each year (Fig. 2). Groundwater exploitation in the basin was negligible, therefore, it was assumed that the long-term change in groundwater storage equalled zero, resulting in $S_{g0} = S_{g\ \mathrm{final}}$ (the end of the running period, December 1998).

To test the modified T–M model, the monthly calculated outflow was compared to the monthly observed outflow at three gauging stations (Koto Baru, Bandar Pandung, and Saruaso) (Fig. 1) for the 1985–1998 period. Fair agreement between the calculated and observed outflows (Fig. 5) indicates that the modified T–M model on a monthly basis is appropriate for this basin. Annual water balance presented in Table 3 reveals that the estimated outflows (baseflows) differed 2–25% (absolute values) from observed outflows with the average absolute difference of 9, 10, and 16% at the Koto Baru, Bandar Pandung, and Saruaso gauging stations, respectively. Moreover, the cumulative estimated and observed outflows at the Koto Baru and Saruaso stations for the period of 1992–1998 differed by 4%, while those at the Bandar Pandung station for the period of 1990–1998 differed by 6%. These results show that even though other studies suggest that in order to reduce water balance errors, an accounting period of less than 10 days should be used (Sophocleous, 1991), our modified T–M water balance model performed well with a monthly accounting period (Fig. 5, Table 3) and demonstrated that it was good enough given the simplicity of the model.

Table 3 confirms that areal recharge plays an important role in the overall water balance components as the annual recharge accounts for 13–59% of the total annual precipitation (the only inflow to the system) with a 14 year (1985–1998) arithmetic average of 40%. Simulated recharge patterns (Fig. 6) agree with observations that during most of the year, precipitation exceeds potential evapotranspiration, filling the root zone to capacity and generating groundwater recharge. The recharge varies annually and spatially (Table 3), depending on the history of soil moisture and the timing and amount of precipitation. During relatively wet years (i.e. 1990, 1993, and 1998) the recharge may represent more than 50% of annual precipitation. In contrast, the drought of 1997 resulted in the lowest overall amount of recharge during the study period, which was 13–27% of the total annual precipitation.

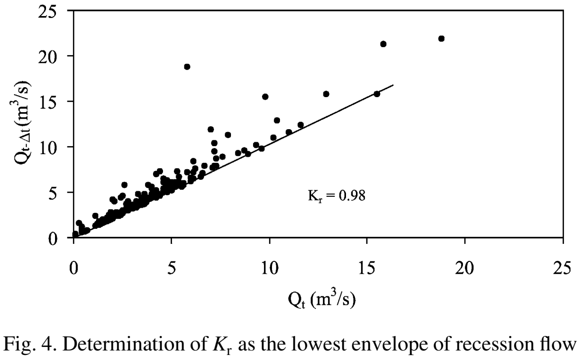

Fig. 4. Determination of K_r as the lowest envelope of recession flow data. $Q_{t-\Delta t}$ and Q_t are successive daily outflows obtained from the Koto Baru River gauging station (the outlet of the Lembang River sub-basin) following at least two successive days without rain.

4.2. Application of the modified water-accounting procedure

4.2.1. Data and methods

We applied the modified M–S water-accounting procedure (Eqs. (6)–(13)) to the Singkarak–Ombilin River basin using annual (calendar year) time steps for

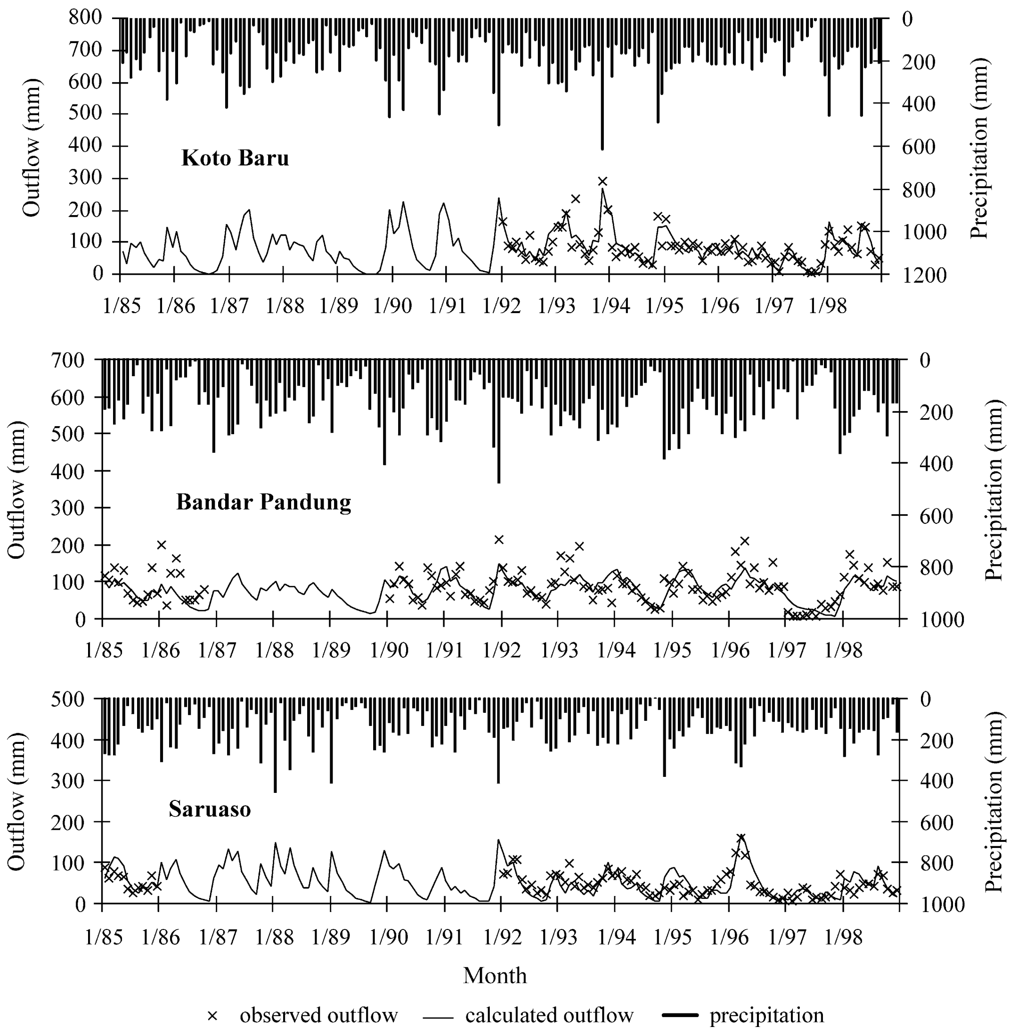

Fig. 5. Observed and calculated outflows at three river gauging stations determined by the modified T–M water balance model.

the period of 1985–1998. Local parameters of each water-accounting component are presented in Table 2, which include annual groundwater recharge and discharge quantities calculated above. Data sources not described previously are given below.

Actual crop and non-crop evapotranspiration was calculated according to the T–M procedure (Thornthwaite and Mather, 1955, 1957). Annual evaporation from free water surfaces (m^3/yr) is a product of the annual pan evaporation rate, a pan coefficient of 0.9, and the surface water area, which is a function of the lake level. Lake areas corresponding to different levels were interpolated from a topographic map with a scale of 1:20,000. When the lake level was not available, a normal lake level was used. Class A pan evaporation from the Danau Diatas and Saning Bakar climatology stations (Fig. 1) were used for Dibawah and Singkarak Lakes, respectively. Evaporation from springs and ponds was assumed to be negligible because their surface areas are less than 0.05% of the areas of Singkarak and Dibawah Lakes.

Daily Singkarak Lake levels, withdrawals from Singkarak Lake for hydropower, and discharge to the Ombilin River, obtained from the State Electrical Power Company, Division III, West Sumatra, were

Table 3
Annual modified Thornthwaite–Mather water balance

Gauging station	Year	Vadose zone[a]				Saturated zone[a]			Observed outflow (mm)	Difference[b] (%)	Recharge as % of Prec. (%)
		Precipitation (mm)	Actual ET (mm)	Recharge (mm)	ΔS_{sm} (mm)	Recharge (mm)	Baseflow (mm)	ΔS_g (mm)			
Koto Baru	1985	2288	1363	939	−14	939	837	101			41
	1986	1722	1038	672	13	672	548	124			39
	1987	2440	1117	1324	−1	1324	1341	−17			54
	1988	1814	972	875	−33	875	970	−95			48
	1989	1916	1107	778	31	778	516	262			41
	1990	2530	1171	1362	−3	1362	1303	58			54
	1991	2046	1077	970	0	970	920	49			47
	1992	2027	1051	986	−11	986	1101	−115	972	13	49
	1993	2988	1216	1773	−1	1773	1672	100	1699	−2	59
	1994	2502	1497	1007	−3	1007	1023	−15	874	17	40
	1995	2277	1239	1039	0	1039	1082	−43	1064	2	46
	1996	1869	1110	788	−30	788	837	−48	817	2	42
	1997	1560	1120	416	24	416	373	43	471	−21	27
	1998	2740	1525	1219	−3	1219	1203	16	1138	6	44
Bd. Pandung	1985	2139	1320	819	0	819	940	−121	1071	−12	38
	1986	1762	1114	649	−1	649	623	26			37
	1987	2156	1115	1043	−1	1043	993	50			48
	1988	1833	987	867	−21	867	981	−114			47
	1989	1881	1174	689	19	689	517	172			37
	1990	2346	1206	1144	−3	1144	1029	115	1067	−4	49
	1991	2109	1099	1012	−2	1012	963	49	1091	−12	48
	1992	1967	1236	732	−1	732	984	−252	1071	−8	37
	1993	2733	1340	1394	−1	1394	1219	175	1267	−4	51
	1994	2020	1307	713	0	713	877	−163	858	2	35
	1995	2670	1476	1196	−1	1196	1159	37	945	23	45
	1996	2167	1076	1092	−2	1092	1186	−94	1460	−19	50
	1997	1510	1309	202	−1	202	309	−108	297	4	13
	1998	2474	1089	1385	1	1385	1156	228	1357	−15	56
Saruaso	1985	2116	1327	789	0	789	753	36	648	16	37
	1986	1783	1126	660	−3	660	619	41			37
	1987	1957	1082	913	−37	913	944	−32			47
	1988	2082	1185	873	23	873	899	−25			42
	1989	1743	948	785	10	785	607	177			45
	1990	1756	1169	589	−1	589	662	−74			34
	1991	1805	1251	556	−3	556	441	116			31
	1992	1798	1327	487	−16	487	626	−140	728	−14	27
	1993	1721	1193	542	−14	542	556	−15	718	−23	31
	1994	1629	1099	511	19	511	481	30	552	−13	31
	1995	1849	1489	363	−3	363	463	−101	457	2	20
	1996	2003	1242	761	−1	761	784	−23	689	14	38
	1997	1665	1426	243	−4	243	248	−5	314	−21	15
	1998	2069	1425	648	−3	648	635	14	507	25	31

Years begin on January 1 and end on December 31. Precipitation and evapotranspiration were measured; groundwater recharge, ΔS_{sm} (soil moisture changes), baseflow, and ΔS_g (groundwater storage changes) were model calculated.

[a] Due to rounding, total inflows may not equal the sums of outflows and storage changes.

[b] The difference of estimated outflows (baseflows) with respect to observed outflows.

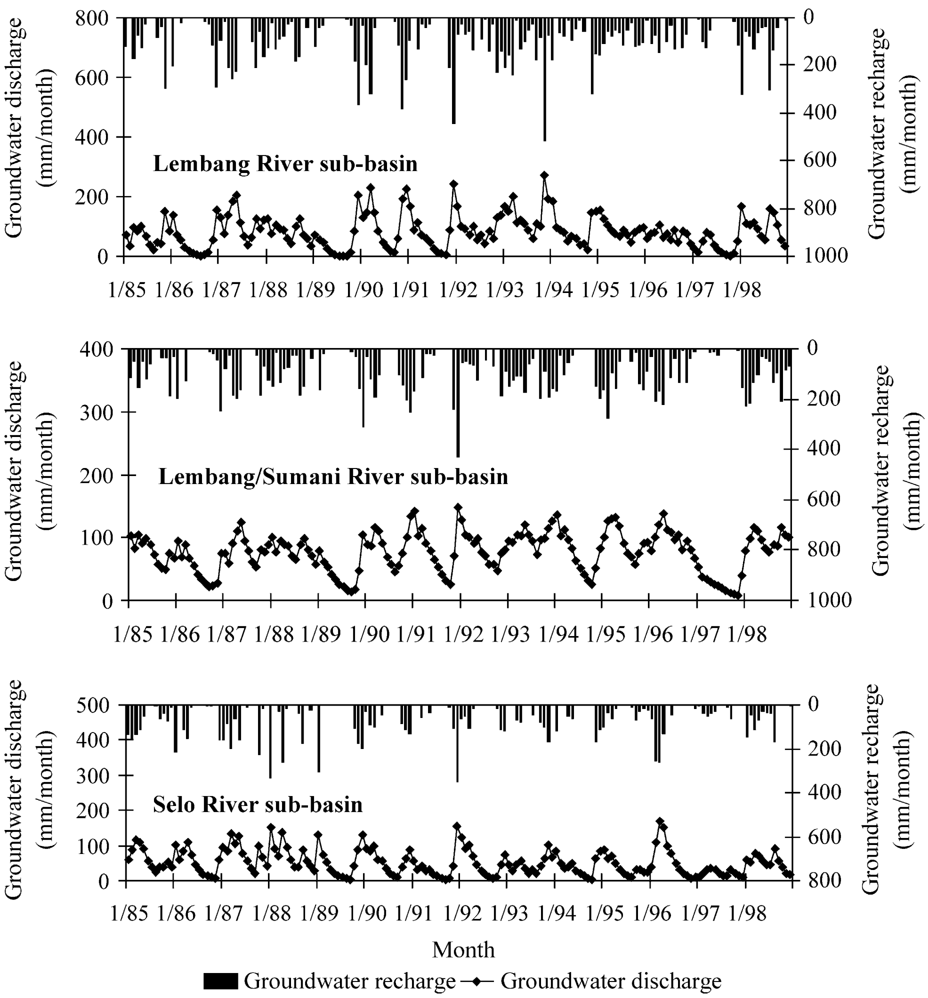

Fig. 6. Estimated groundwater discharge and groundwater recharge in three river sub-basins determined by the modified T–M water balance model.

available for June 1998–November 1999. The lake level data indicate insignificant changes from the beginning of a year to the beginning of the next year, and over a long term the changes in the lake level are insignificant compared to the overall water balance components. Therefore, it was assumed that during the period 1985–1998 annual changes in the Singkarak Lake level were negligible in the overall water balance components. No data were available for changes in the Dibawah Lake levels, which were assumed to be insignificant.

Livestock and domestic water consumption was based on national per capita consumption rates. According to the Directorate General of Human Settlements, Ministry of Public Works, Provincial Planning and Development Board, and local and provincial water supply enterprises, average non-domestic water consumption (commercial and small-scale industrial uses) ranged from 13 to 21% of the total domestic water consumption. Water consumption by large-scale industries, such as the Ombilin coal-washing plant, the Ombilin and Salak thermal power plants, and the AMIA bottled water industry, was obtained directly from industry officials. Based on a local survey, livestock, domestic (household activities), and non-domestic (commercial and industrial activities) water depletion was assumed to be 10, 10, and 20%, respectively, of total water consumption of each use. The rest was returned as wastewater.

Outflow from Singkarak Lake was calculated by subtracting the lake evaporation from the sum of inflows and precipitation to the lake. Since the Singkarak HEPP began diverting water in May 1998, outflow from the lake has been regulated at 2, 2, and 6 m^3/s during the wet, normal, and dry months, respectively (West Sumatra Governor Decree No. SK.669.1-565-1998). This regulated outflow was used downstream (Ombilin River sub-basin) for irrigation, domestic water supply, the Ombilin coal-washing plant, and the Ombilin and Salak thermal power plants. Since there was no information available about downstream environmental requirements, committed outflow from the Singkarak sub-basin was calculated based on the need for regulated outflow only and no committed outflow from the Ombilin River sub-basin was assumed. Non-utilizable outflow was not identified.

4.2.2. Results

Water use patterns and indicators were determined for three different periods: 1985–1996 ('normal' conditions with the average of 214 cm of precipitation), 1997 (extremely dry year with 174 cm of precipitation), and 1998 (onset of withdrawals for the Singkarak HEPP) and the wettest year, with 286 cm of precipitation). Four scenarios were analyzed for 1985–1998. The first scenario is the actual condition for 1985–1998, in which the Singkarak HEPP diverted 682 million m^3 from the basin, beginning in May 1998. The second represents a possible future scenario by duplicating 1985–1998 climatic conditions, but assuming that hydropower diversions began in 1985. For this scenario, we assumed that the average discharge from Singkarak Lake to the Ombilin River was 6 m^3/s from June to September (dry months) and 2 m^3/s for other months and that average withdrawal for hydropower was at its guaranteed discharge of 37.2 m^3/s (State Electrical Power Company, 1998). The third scenario is similar to the second one with the addition that downstream field irrigation was increased during the wet months (January–April), which consequently enhanced flows during the dry months (June–September) as explained earlier. The last scenario is similar to the second one with the addition that the downstream irrigated area during the dry months (June–September) was increased to increase or maximize beneficial utilization.

We calculated five *water-accounting indicators* to help identify opportunities for improving water management. The first four were adopted from Molden and Sakthivadivel (1999); the fifth indicator was developed for this study. The selected indicators are

- Depleted fraction of gross inflow

$$\mathrm{DF}_{\mathrm{gross}} = D/I_{\mathrm{g}} = (D_{\mathrm{p}} + D_{\mathrm{nb}} + D_{\mathrm{nn}})/I_{\mathrm{g}} \tag{19}$$

- Depleted fraction of available water

$$\mathrm{DF}_{\mathrm{available}} = D/A = (D_{\mathrm{p}} + D_{\mathrm{nb}} + D_{\mathrm{nn}})/A \tag{20}$$

- Process fraction of available water

$$\mathrm{PF}_{\mathrm{available}} = D_{\mathrm{p}}/A \tag{21}$$

- Beneficial utilization of available water

$$\mathrm{BU}_{\mathrm{available}} = D_{\mathrm{b}}/A = (D_{\mathrm{p}} + D_{\mathrm{nb}})/A \tag{22}$$

- Potential beneficial utilization of available water

$$\mathrm{PBU}_{\mathrm{available}} = D_{\mathrm{pb}}/A = R/A \tag{23}$$

where I_g is the gross inflow; D, the water depletion; D_p, the process depletion; D_{nb}, the non-process, beneficial depletion; D_{nn}, the non-process, non-beneficial depletion; A, the available water; D_b, the beneficial depletion; D_{pb} is the potential beneficial depletion, which in this basin is the amount of groundwater recharge, R.

Depleted fraction indicates the fraction of either inflow or available water that is depleted. *Beneficial utilization* indicates the fraction of available water that is beneficially depleted, where *beneficial depletion* produces a good or fulfills a beneficial need and is either *process* or *non-process depletion*, and *available water* is defined as net inflow less non-utilizable outflow and the amount of water set aside for committed uses outside of the domain. Net inflow is gross inflow plus any changes in storage. The distinction between non-beneficial and beneficial depletion is critical. For example, evapotranspiration from phreatophytes might be beneficial if they serve as a buffer zone around a lake, but non-beneficial if the depletion does not meet environmental needs. $PBU_{available}$ indicates how much available, but currently unused, water can potentially be depleted beneficially. In this basin, $PBU_{available}$ represents how much groundwater recharge is potential for use. All indicators are expressed as fractions.

4.2.3. Scenario 1: water accounting of the Singkarak–Ombilin river basin, 1985–1998

Table 4 summarizes water use and indicators for 1985–1998. The indicator of $DF_{available}$ shows that even during the drought of 1997, some excess water was available for further uses. Specifically, $DF_{available}$ indicates that 57–81% of the available water in the Singkarak–Ombilin River basin was depleted, leaving 19–43% for further use. Hence, the Singkarak–Ombilin River basin and its sub-basins were open basin/sub-basins (Molden, 1997; Molden and Sakthivadivel, 1999), meaning an uncommitted utilizable flow existed that can be depleted within the domain.

The amount of available water that was depleted by process uses, $PF_{available}$, in the entire basin ranged from 0.24 to 0.38, indicating water depleted by process uses was low. Water use effectiveness in the basin was low, as indicated by $BU_{available}$ ranging from 0.37 to 0.52, meaning that only about 37–52% of the available water was beneficially depleted. The other 48–63% was depleted mostly by evapotranspiration from shrubs/bush and fallow. Economic and population pressures (population density in the basin was about 2.5 times that of the West Sumatra Province) have led to extensive areas of fallow associated with slash-and-burn practices and shifting cultivation.

$PBU_{available}$ indicates that 19–41% of total available water recharges the aquifer. Before discharging to rivers as baseflow, this recharge is stored in the aquifer and can be potentially depleted for beneficial purposes. Under current conditions, all of the groundwater eventually discharges to rivers, which flow out of the basin, becoming unutilized outflow within the basin (utilizable for downstream users out of the basin). However, some of the stored groundwater can be potentially exploited for irrigation within the basin. This water, which previously discharged from the basin, would now be depleted beneficially within the basin, as evapotranspiration from crops. In this way, water would be used more productively within the basin, and unutilized outflow would be reduced. This option is especially attractive for the Ombilin River sub-basin after the start of the Singkarak HEPP because, in contrast to surface water, which is fully utilized, groundwater is still available during the dry period (see Scenario 4). It should be noted that the groundwater recharge could also be potentially used for other beneficial uses within the basin as well as for environmental commitment downstream outside the basin (i.e. to maintain fisheries, prevent the river from carrying out pollutants that would otherwise concentrate in the stream). However, lack of definition and information regarding these uses made it impossible to take the uses into account.

4.2.4. Scenario 2: predicted water accounting of the Singkarak–Ombilin river basin after diversion to the Singkarak HEPP

Table 5 summarizes predicted future water use and indicators, assuming 37.2 m^3/s of water is diverted annually to the Singkarak HEPP under 1985–1998 climate conditions. In this scenario, during an extremely dry year like 1997, depletion would exceed gross inflow, as indicated by DF_{gross} of 1.12 and 1.25 for the entire basin and for the Singkarak sub-basin, respectively. This overdraft was not permanent since it would be made up in the next year, as shown by DF_{gross} of 0.77 and 0.81 for the respective basins in 1998. Water depletion in excess of gross inflow would come from unsustainable water withdrawal from Singkarak Lake. Recently, conflicts between the local community and government have arisen over the use of additional land exposed by the declining lake level.

Under the predicted future scenario, available water in the Singkarak–Ombilin River basin would be nearly depleted, as indicated by $DF_{available}$ of 0.81–0.95 (Table 5). Thus, overall the basin would be in transition from an open to a closing basin. Looking into the sub-basin level, water resources in the Singkarak sub-basin would be fully utilized ($DF_{available} = 1$), as all excess flow to Singkarak Lake was withdrawn for the Singkarak HEPP. Clearly, there would no scope for increased depletion

Table 4
Water accounting of the Singkarak–Ombilin River basin, 1985–1998 (Scenario 1)

Components	Singkarak sub-basin			Ombilin River sub-basin			Singkarak–Ombilin River basin		
	1985–1996	1997	1998	1985–1996	1997	1998	1985–1996	1997	1998
Inflow	Water use (million m³/year)								
Gross inflow	*2612*	*2065*	*3926*	*3366*	*2423*	*3534*	*4739*	*3855*	*6320*
Precipitation	2612	2065	3926	2127	1790	2394	4739	3855	6320
Surface flow	0	0	0	1239	633	1141	0	0	0
Storage change[a]	−11	26	91	−5	−40	64	−16	−14	155
Soil moisture change	−1	−1	0	−3	−34	28	−4	−35	28
Lake storage change	0	0	0	0	0	0	0	0	0
Groundwater storage change	−10	27	91	−2	−6	36	−12	21	126
Net Inflow	*2623*	*2039*	*3835*	*3371*	*2463*	*3470*	*4755*	*3869*	*6165*
Depletion	*1384*	*1406*	*2695*	*1312*	*1719*	*1695*	*2696*	*3125*	*4389*
Process[a]	503	494	1435	638	909	893	1141	1403	2328
ET from agricultural crops	502	493	752	636	906	891	1138	1399	1643
Dom. non-dom. livestock[b]	1	1	683	2	2	2	3	4	685
Non-process beneficial (forest)	370	350	483	234	250	236	604	600	719
Non-process non-beneficial	511	561	777	439	560	565	950	1122	1342
Total beneficial	873	845	1918	873	1159	1130	1746	2003	3047
Outflow	*1239*	*633*	*1221*	*2059*	*744*	*1776*	*2059*	*744*	*1776*
Committed	0	0	80	0	0	0	0	0	80
Uncommitted utilizable	1239	633	1141	2059	744	1776	2059	744	1695
Uncommitted non-utilizable	0	0	0	0	0	0	0	0	0
Groundwater recharge	1118	611	1684	818	104	671	1936	716	2356
Available water	2623	2039	3755	3371	2463	3470	4755	3869	6085
Indicators									
DF_{gross}	0.54	0.68	0.69	0.39	0.71	0.48	0.57	0.81	0.69
$DF_{available}$	0.54	0.69	0.72	0.39	0.70	0.49	0.57	0.81	0.72
$PF_{available}$	0.19	0.24	0.38	0.19	0.37	0.26	0.24	0.36	0.38
$BU_{available}$	0.34	0.41	0.51	0.26	0.47	0.33	0.37	0.52	0.50
$PBU_{available}$	0.43	0.30	0.45	0.25	0.04	0.19	0.41	0.19	0.39

[a] Due to rounding, totals may not equal sums of values.
[b] Livestock depletive use ranged from 0.03 to 0.012 million m³/yr.

and reduced outflow to Singkarak Lake, as that would cause unsustainable lake level changes. Although there is no clear water allocation rule in the upstream, higher priority was given to hydropower than to agriculture. Therefore, an opportunity for increasing water productivity in the agricultural sector could be by regenerating soil fertility and controlling weeds, thus reducing non-beneficial evaporative depletion by converting fallow, bush, and shrubs to cropland. Other options are to switch to less water-demanding crops or to cultivate fewer but economically more valuable crops.

In contrast to the Singkarak sub-basin, the Ombilin River sub-basin (downstream) would remain open, even if the Singkarak HEPP continues to divert 37.2 m^3/s outside the basin (Table 5). Thus, opportunities for more water supplies could be safely developed without harm to downstream uses. For example, by utilizing excess surface water to reduce outflow downstream (Scenario 3), or tapping into groundwater storage (Scenario 4), as $PBU_{available}$ indicates about 5–37% of available water is recharge (Table 5), which can be retained in the aquifer for months (Fig. 6), during which it

Table 5
Water accounting of the Singkarak–Ombilin River basin, after assuming 37.2 m^3/s diverted annually from Singkarak Lake to the Singkarak HEPP (Scenario 2)

Components	Singkarak sub-basin			Ombilin river-basin			Singkarak–Ombilin river basin		
	1985–1996	1997	1998	1985–1996	1997	1998	1985–1996	1997	1998
Inflow	Water use (million m^3/year)								
Gross inflow	2612	2065	3926	2232	1895	2499	4739	3855	6320
Precipitation	2612	2065	3926	2127	1790	2394	4739	3855	6320
Surface flow	0	0	0	105	105	105	0	0	0
Storage change[a]	−50	−619	634	−5	−40	64	−55	−659	698
Soil moisture change	−1	−1	0	−3	−34	28	−4	−35	28
Lake storage change	−39	−645	544	0	0	0	−39	−645	544
Groundwater storage change	−10	27	91	−2	−6	36	−12	21	126
Net Inflow	2663	2684	3292	2237	1935	2435	4795	4514	5622
Depletion	2557	2579	3186	1312	1719	1695	3869	4298	4881
Process[a]	1676	1667	1926	638	909	893	2315	2576	2819
ET from agricultural crops	502	493	752	636	906	891	1138	1399	1643
Dom. non-dom. livestock[b]	1174	1174	1174	2	2	2	1176	1177	1177
Non-process beneficial (forest)	370	350	483	234	250	236	604	600	719
Non-process non-beneficial	511	561	777	439	560	565	950	1122	1342
Total beneficial	2046	2018	2409	873	1159	1130	2919	3177	3539
Outflow	105	105	105	926	216	740	926	216	740
Committed	105	105	105	0	0	0	0	0	80
Uncommitted utilizable	0	0	0	926	216	740	926	216	660
Uncommitted non-utilizable	0	0	0	0	0	0	0	0	0
Groundwater recharge	1118	611	1684	818	104	671	1968	673	2245
Available water	2557	2579	3186	2237	1935	2435	4795	4514	5541
Indicators									
DF_{gross}	1.00	1.25	0.81	0.59	0.91	0.68	0.82	1.12	0.77
$DF_{available}$	1.00	1.00	1.00	0.59	0.89	0.70	0.81	0.95	0.88
$PF_{available}$	0.66	0.65	0.60	0.28	0.47	0.37	0.48	0.57	0.51
$BU_{available}$	0.80	0.78	0.76	0.39	0.60	0.46	0.61	0.70	0.64
$PBU_{available}$	0.44	0.24	0.53	0.37	0.05	0.28	0.41	0.15	0.41

[a] Due to rounding, totals may not equal sums of values.
[b] Livestock depletive use ranged from 0.03 to 0.012 million m^3/yr.

can be potentially used beneficially. Both options are explored below.

4.2.5. Scenario 3: increasing downstream irrigation during the wet months (January–April)

The unique advantage of the shallow aquifer in the Ombilin River sub-basin offers an alternative of using groundwater and surface water conjunctively by expanding the irrigated area to utilize excess surface water during the wet months (January–April). Instead of immediately draining from the basin, the excess irrigation water would infiltrate through irrigated fields to the aquifer, resulting in increased groundwater recharge. Eventually, this groundwater would discharge to rivers, increase the river water level during the dry months (June–September), and potentially be used for irrigating dry season crops and have other beneficial uses. We will examine this alternative and evaluate its performance with respect to its final outflows.

The modified T–M monthly time step water balance model was used to simulate the above alternative. It was assumed that the hydropower has taken place since 1985. Therefore, in addition to

Table 6
Downstream groundwater balance for wet (January–April) and dry (June–September) months of Scenarios 2 and 3 (million m^3)

Scenario[a]	Recharge		Groundwater discharge				Groundwater Storage change		Outflow[b]	
	Wet	Dry	Irrigation		Net discharge[c]		Wet	Dry	Wet	Dry
			Wet	Dry	Wet	Dry				
1985–1996(2)	456.6	32.0	0.0	0.0	423.7	132.1	33.0	−100.1	444.5	195.4
1985–1996(3)	948.8	32.0	483.7	0.0	253.9	228.4	211.2	−196.3	274.7	291.6
Change (%)	107.8	0.0			−40.1	72.9	541.0	−96.2	−38.2	49.3
1997(2)	75.8	0.7	0.0	0.0	65.7	24.2	10.1	−23.5	86.4	87.5
1997(3)	303.5	0.7	229.2	0.0	0.0	71.6	74.3	−70.9	0.0	134.8
Change (%)	300.4	0.0			−100.0	195.2	632.8	−201.0	−100.0	54.1
1998(2)	327.4	343.2	0.0	0.0	211.6	270.8	115.8	72.4	232.3	334.0
1998(3)	785.5	343.2	457.6	0.0	39.7	368.3	288.2	−25.1	50.2	431.5
Change (%)	139.9	0.0			−81.2	36.0	148.9	−134.7	−78.4	29.2

Scenario 2 is a possible future scenario after diversion to the Singkarak HEPP. Scenario 3 is similar to Scenario 2 with the addition of increased irrigation during the wet months.

[a] Numbers in brackets indicate scenario.

[b] Outflow is the sum of groundwater discharge and regulated surface flow from Singkarak Lake at 2 and 6 m^3/s for wet and dry years, respectively.

[c] Net discharge is total groundwater discharge minus withdrawal for irrigation.

the assumptions made in Scenario 2, during the wet months (January–April) of each simulated year (1985–1998), the irrigated area was expanded from an existing average of 5% (Table 1) to 34% of the total downstream area, simulated by irrigating not only a ‘dry land rice field’, but also a ‘rainfed rice field’ and ‘other field crops’. Increased irrigation water demand was supplied by the excess surface flows that were always available during the wet months of January–April. The irrigation water requirement for all crops was based on the local standard, which was 1.1 l/ha/s (Sugianto, 2000, personal communication). Total outflow was the sum of groundwater discharge (baseflow) calculated from the modified T–M model and regulated surface flow from Singkarak Lake (2–6 m^3/s).

The groundwater balance presented in Table 6 indicates that the recharge, which is the potential for beneficial depletion, during the wet months (January–April) would rise by 108, 300, and 140% for 1985–1996, 1997, and 1998, respectively, from that of Scenario 2. The results show that groundwater discharge during the dry months (June–September) would increase by 73, 195, and 36% for 1985–1996, 1997, and 1998, respectively, from that of Scenario 2, and total outflow at the downstream outlet during the dry months would increase by 49, 54, and 29% for 1985–1996, 1997, and 1998, respectively.

4.2.6. Scenario 4: increasing irrigation downstream during the dry months (June–September)

After the Singkarak HEPP began operation, it was predicted that only limited excess surface flow would be available downstream during the dry months (June–September), as described in Scenario 2. Given land use and its cultivated crops remain unchanged, an option to increase water beneficial utilization during the dry months is by tapping into groundwater storage and using the groundwater supply for irrigating more dry season crops.

The modified T–M monthly water balance model was used for the 1985–1998 period to simulate the above option. As mentioned in Scenario 3, it was assumed that the hydropower has taken place since 1985. During the dry months of June–September, the irrigated area was expanded from the original 5–34% of the total downstream land with an irrigation water requirement of 1.1 l/ha/s (Sugianto, 2000, personal communication). The irrigated fields were a ‘dry land rice field’, ‘rainfed rice field’, and ‘other field crops’ with an average percentage of total land available

Table 7
Downstream water balance for dry months (June–September) of Scenarios 2 and 4 (million m^3): (a) vadose zone, (b) above groundwater zone

(a) Vadose zone

Scenario[a]	Inflow			Depletion		Outflow Recharge	Soil moisture storage change
	Precipitation	Surface flow	Groundwater irrigation	Beneficial	Non-beneficial		
1985–1996 (2)	431	57	0	287	145	32	− 34
1985–1996 (4)	431	57	558	307	145	563	− 26
1997 (2)	457	57	0	355	172	1	− 71
1997 (4)	457	57	227	372	172	205	− 66
1998 (2)	913	57	0	377	188	343	5
1998 (4)	913	57	648	378	188	990	5

(b) Above groundwater zone

Scenario[a]	Recharge	Groundwater pumping	Groundwater discharge	Storage change
1985–1996 (2)	32	0	132	− 100
1985–1996 (4)	563	558	110	− 106
1997 (2)	1	0	24	− 24
1997 (4)	205	227	5	− 27
1998 (2)	343	0	271	72
1998 (4)	990	648	269	73

Scenario 2 is a possible future scenario after diversion to the Singkarak HEPP. Scenario 4 is similar to Scenario 2 with the addition of increased irrigation during the dry months.
[a] Numbers in brackets indicate scenario.

downstream as 5, 7, and 22%, respectively (Table 1). In order to avoid long-term overdraft, it was assumed that the volume of groundwater storage could not be withdrawn below the naturally occurring dry month storage volume (i.e. the height of the water table above a reference level, h_t, could not be negative after groundwater withdrawal).

Results indicate that by expanding the irrigated area during the dry months, beneficial utilization downstream would increase by 7% from Scenario 2 (Table 7). In an exceptionally dry year like 1997, this scenario demonstrates that it remained viable to increase beneficial utilization by irrigating more dry season crops. During the dry months, the given groundwater discharge is insignificant compared to the overall water balance components (Table 7). The outflow in the river would largely depend on the supply from Singkarak Lake ($6\ m^3/s$), as total outflow to the river downstream is the sum of groundwater discharge and surface flow from the lake.

An overall summary of downstream water accounting indicators and outflow for Ombilin River sub-basin across all scenarios is presented in Table 8. In terms of relative water use performance, results show that, in general, Scenario 4 contributes to the highest indicator performance and the least unutilized (within the basin) outflow among all the scenarios.

5. Discussion

Clearly, water should not be depleted beyond the limit set by the available water. The reliability of water availability estimates depends on the accuracy of individual water balance components. In the original M–S water-accounting examples, groundwater levels are known, or groundwater storage change can be assumed negligible (Molden, 1997; Molden et al., 2001). Combining groundwater and surface water into a single domain may provide a good estimate of available water; however, the importance of groundwater cannot be identified, and this can only be ignored if groundwater exploitation is negligible. In cases where it is known that

Table 8
Downstream water-accounting indicators and outflow for all scenarios

Components	Scenario 1			Scenario 2			Scenario 3			Scenario 4		
	1985–1996	1997	1998	1985–1996	1997	1998	1985–1996	1997	1998	1985–1996	1997	1998
DF_{gross}	0.39	0.71	0.48	0.59	0.91	0.68	0.60	0.92	0.69	0.61	0.94	0.69
$DF_{available}$	0.39	0.70	0.49	0.59	0.89	0.70	0.60	0.90	0.70	0.60	0.92	0.70
$PF_{available}$	0.19	0.37	0.26	0.28	0.47	0.37	0.29	0.48	0.38	0.30	0.50	0.37
$BU_{available}$	0.26	0.47	0.33	0.39	0.60	0.46	0.40	0.61	0.47	0.41	0.63	0.47
$PBU_{available}$	0.25	0.04	0.19	0.37	0.05	0.28	0.59	0.17	0.46	0.61	0.16	0.54
Outflow ($\times 10^6$ m^3/yr)	2059.37	743.53	1775.76	925.56	215.58	740.41	905.95	196.55	718.34	886.46	162.24	721.99

Scenario 1 is the actual condition of 1985–1998, in which 682 million m^3 of water was diverted from the upper sub-basin to the Singkarak HEPP, beginning in May 1998. Scenario 2 is a possible future scenario by duplicating 1985–1998 climatic conditions, but assuming that the diversion of 37.2 m^3/s to the Singkarak HEPP began in 1985. Scenario 3 is similar to Scenario 2 with the addition of increased irrigation downstream during the wet months (January–April). Scenario 4 is similar to Scenario 2 with the addition of increased irrigation downstream during the dry months (June–September).

groundwater components play an important role in the overall water balance, such as in this basin, explicit analysis of groundwater is critical. In the Singkarak–Ombilin River basin, groundwater storage could supplement the current water supply. Our separation of groundwater and surface water in the water-accounting procedure, involving a simple monthly groundwater balance model, offers a more realistic estimate of water availability and a more realistic approach in saving water from discharging outside the basin as revealed in Scenarios 3 and 4 (Tables 6 and 7). Given the minimal hydrogeologic data available, the groundwater balance model itself could provide useful insights on groundwater flow mechanism in the basin.

As found in many other basins, there are uncertainties in the water accounting computations of this basin. For example, errors in the measurement of precipitation and evaporation, missing data, and there may be minor groundwater exploitation and lake level changes which we have assumed to be negligible. In our case, outflow was the closure of water balance, calculated by subtracting total water depletion from the net inflow. Consequently, the accuracy of the closure term is associated with the accuracy of other terms entering the water balance. We carefully tried to estimate the accuracy of the closure term presented in Table 4 by following the methodology proposed by Clemmens and Burt (1997). Precipitation was assumed with 10% confidence interval, evaporation with 15%, and other components and coefficients with 10%. The confidence interval equalled twice the coefficient of variation of a normal (Gaussian) distribution. Under these assumptions, the average confidence interval of the outflow was estimated to be $\pm 21\%$. Despite this accuracy level, the finding remains that outflow is a major component in the overall water balance and, accordingly, a similar finding also holds for groundwater recharge, as it is the key contributor to the outflow in this basin.

6. Conclusions

The Molden and Sakthivadivel water accounting procedure has proven very useful for analyzing water use patterns and identifying opportunities for improving water management within a basin. When groundwater is an important component of the overall water balance, ground and surface water separation can improve water availability estimation and provide a more realistic approach for water savings. Although the precise mechanisms of groundwater flow through the Singkarak–Ombilin River basin are not clearly understood, our modified Thornthwaite–Mather water balance model generated plausible groundwater recharge and discharge data for explicit water-accounting analysis. Results of the water-accounting analysis show that the basin is in transition from an *open basin* (additional water is available for use) to a *closing basin* (nearly no more water is available for use). After diversions to the Singkarak Hydro Electric Power Plant (HEPP) began in 1998, the amount of water that was not available for other uses, such as for irrigation, was envisaged to increase from 57–81 to 81–95% of water available for use in the basin. In the downstream, with nearly all water supplies fully utilized during the dry months (June–September), the modified water accounting demonstrates that tapping water from a shallow, unconfined aquifer during the dry months is an appealing way for increasing water beneficial utilization, while the use of groundwater and surface water conjunctively during the wet months (January–April) reveals an attractive approach for increasing water supply and beneficial utilization.

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