Table 3.17 Monthly multiplier used for evapotranspiration per land-cover type

Mth	Bare soil	Dry deciduous forest	Hill evergreen forest	Water ody	Mixed deciduous forest	Pine forest	Crop land	Paddy Field	Urban
Jan	0.60	0.80	1.00	1.00	1.00	1.00	1.00	1	0.01
Feb	0.60	0.80	1.00	1.00	1.00	1.00	1.00	1	0.01
Mar	0.60	0.60	1.00	1.00	1.00	1.00	0.70	0.8	0.01
Apr	0.60	0.60	1.00	1.00	1.00	1.00	0.70	0.6	0.01
May	0.60	1.00	1.00	1.00	1.00	1.00	0.70	0.6	0.01
Jun	0.60	1.00	1.00	1.00	1.00	1.00	0.70	0.6	0.01
Jul	0.60	1.00	1.00	1.00	1.00	1.00	0.70	0.6	0.01
Aug	0.60	1.00	1.00	1.00	1.00	1.00	0.70	0.6	0.01
Sep	0.60	1.00	1.00	1.00	1.00	1.00	0.70	0.6	0.01
Oct	0.60	1.00	1.00	1.00	1.00	1.00	0.70	0.6	0.01
Nov	0.60	1.00	1.00	1.00	1.00	1.00	1.00	1	0.01
Dec	0.60	1.00	1.00	1.00	1.00	1.00	1.00	1	0.01

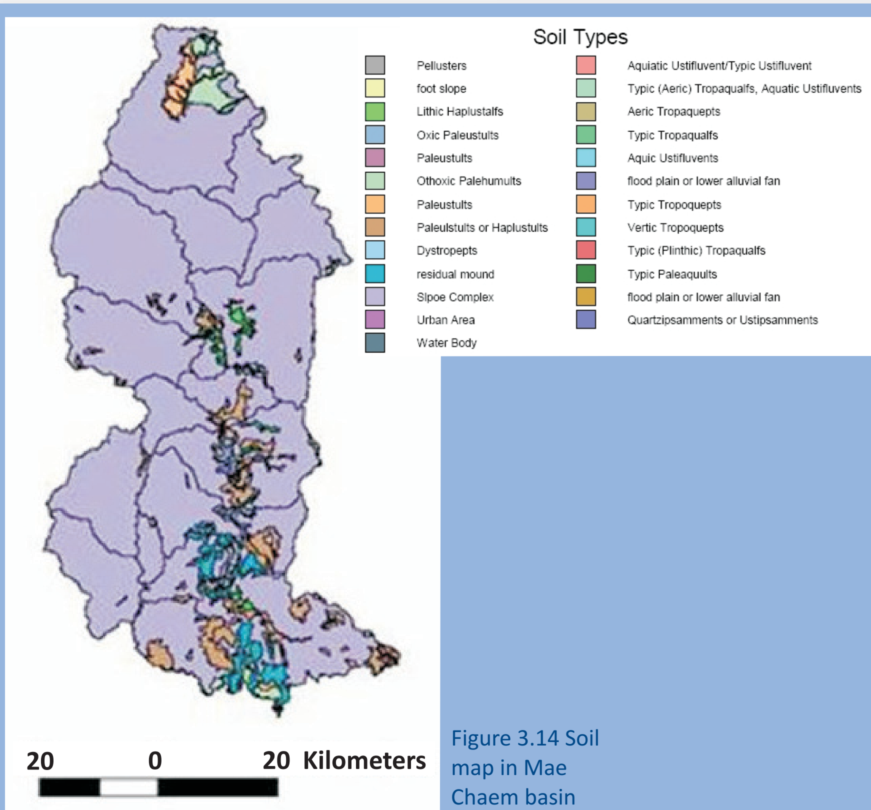

Figure 3.14 Soil map in Mae Chaem basin

Soil types

Main soil types in Mae Chaem area were entisol (91.5%), ultisol (6.2%), alfisol (2.1%) and inceptisol (0.16%) (Table 3.18). The distribution over the subcatchments is presented in Figure 3.14. (www.trfic.msu.edu/products/seasia_products/LUCC/thailand_lucc/phase1/soil.html)

Table 3.18 Main soil order of Mae Chaem subcatchments

Subcatchment/soil	Entisols	Alfisol	Inceptisol	ultisol
1	1.00	0.00	0.00	0.00
2	1.00	0.00	0.00	0.00
3	1.00	0.00	0.00	0.00
4	0.98	0.01	0.01	0.00
5	0.85	0.15	0.00	0.00
6	1.00	0.00	0.00	0.00
7	0.93	0.07	0.00	0.00
8	0.99	0.00	0.01	0.00
9	0.84	0.15	0.00	0.01
10	0.97	0.02	0.00	0.01
11	0.76	0.00	0.00	0.24
12	0.70	0.00	0.00	0.30
13	0.81	0.00	0.00	0.19
14	0.99	0.00	0.00	0.01
15	1.00	0.00	0.00	0.00
16	0.98	0.00	0.00	0.02
17	0.76	0.00	0.00	0.24
18	1.00	0.00	0.00	0.00
19	0.82	0.00	0.01	0.16
Solum Depth (cm)	**147**	**170**	**170**	**180**

Infiltration

The land unit of Mae Chaem is dominated by loamy and clayey soil (Table 3.19) that affects the surface infiltration properties. Surface infiltration is less than 240 mm/day (Table 3.20). Soil BD/BDref per land cover was calculated based on a soil survey (Table 3.21).

Table 3.19 Land unit in Mae Chaem basin (Merrit 2005)

Land unit	Soil texture/description	Slope class*
6	Shallow loam and gravel soils	D or E
8	Shallow loam and gravel soils with 2–10% rock outcrops	A or B
10	Shallow loam and gravel soils with 2–10% rock outcrops	C
12	Shallow loam and gravel soils with 2–10% rock outcrops	D or E
23	Deep loam soils	A or B
25	Deep loam soils	C
27	Deep loam soils	D or E
31	Shallow clay soils	C
35	Shallow clay and gravel soils with 2–10% rock outcrops	C
37	Shallow clay and gravel soils with 2–10% rock outcrops	D or E
45	Deep clayey soils	A or B
46	Deep clayey and gravel soils	A
47	Deep clayey soils	C
48	Deep clayey and gravel soils	B
49	Deep clayey soils	D or E
50	Deep clayey and gravel soils	D or E
55	Medium deep clayey and gravel soils	D or E
88	Deep clayey irrigated paddy soils	A or B
99	Deep clayey paddy soils	A or B

* A: 0–8%, B: 8–16%, C: 16–35%, D: 35–60%, E: >60%

Table 3.20 Infiltration base of reference basic infiltration rates for various soil types (Brouwer 1990)

Soil type	Rate (mm/day)	
Sand	>>	720
Sandy loam	480	720
Loam	240	480
lay loam	120	240
Clay	24	120

Table 3.21 BD/BDref (Unpublished survey results from ICRAF Thailand 2002) LUT BD/BDref

	BD/BDref			
LUT	n	Min	Average	Max
Bare Soil	17	0.73	1.00	1.13
Dry deciduous forest	7	0.84	1.02	1.07
Hill evergreen forest	1	1.11	1.11	1.11
Mixed deciduous forest	9	0.98	1.08	1.18
Pine forest	16	0.92	1.07	1.16
Crop	3	1.10	1.20	1.38
Paddy	5	1.05	1.09	1.13

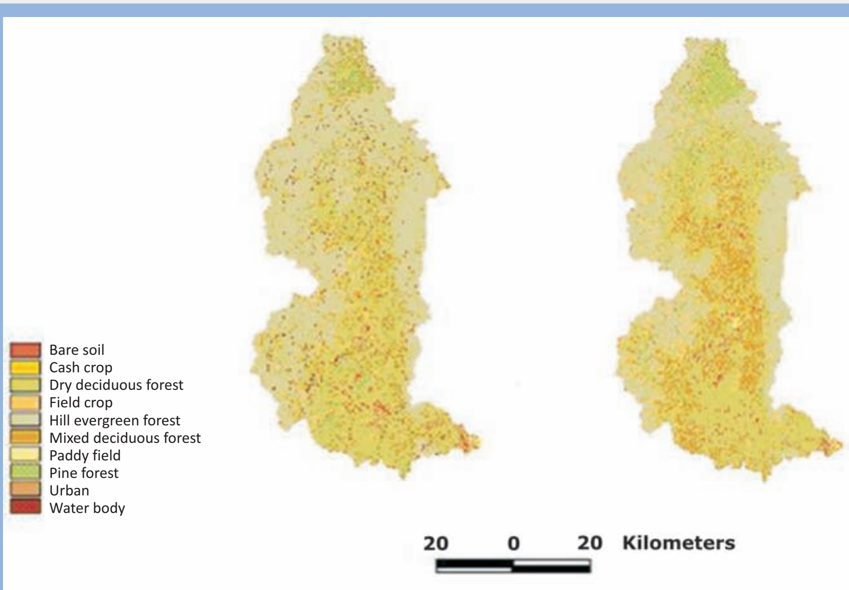

Figure 3.15 Land cover in Mae Chaem basin

Table 3.22 Satellite data for Mae Chaem area (Saipothong *et al.* 2007)

Date	Type	Format	Resolution
3 February,1989	Landsat TM5	BSQ	30
5 March, 2000	Landsat TM7	HDF	15

Table 3.23 Land-use types in Mae Chaem basin based on Landsat image classifications (Classified by ICRAF Thailand)

LUT	Percentage	
	1989	2000
Bare soil	0.7	0.8
Dry deciduous forest	32.6	40.7
Hill evergreen forest	40.4	28.5
Waterbody	1.5	0.0
Mixed deciduous forest	6.3	9.7
Pine forest	7.4	4.7
Crop	10.3	14.9
Paddy	0.5	0.3
Urban	0.4	0.4

Land cover

Available land-cover data of Mae Chaem basin is based on Landsat imagery classifications (Table 3.22). In this study, land-cover data was reclassified into 9 classes (Table 3.23) and we extended the simulation to year 2003 by using year 2000 data.

Subcatchment boundaries

Subcatchment boundaries were generated by tracing the flow direction from the defined outlet back to the beginning cells. We used DEM from SRTM (Shuttle Radar Topographic Mission, http://srtm.csi.cgiar.org). The 19 subcatchments were extracted for this study (Figure 3.16).

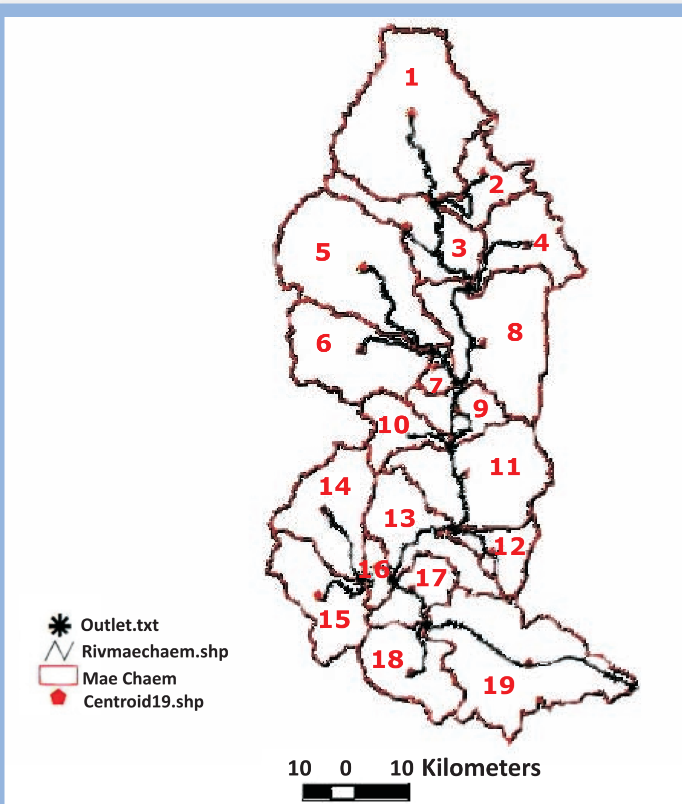

Figure 3.16 Subcatchments of Mae Chaem basin

Stream routing

The routing distance was calculated by measuring the stream length from the stream segment closest to subcatchment centroid to the targeted outlet (Table 3.24).

Table 3.24 Routing distance from centroid point to the outlet

ID	Source thm	Centroid		Outlet		Length km	Observation point km	Area km^2
		X_coord	Y_coord	X_coord	Y_coord			
1	Riv1.shp	425809	2103903	461584	2010588	190.03	23.8	469.97
2	Riv2.shp	437524	2094453	428104	2021238	185.08	18.9	115.79
3	Riv3.shp	424654	2085558	428119	2021238	161.91	20.6	184.26
4	Riv4.shp	444259	2083053	417544	2028573	160.69	19.4	168.42
5	Riv5.shp	417754	2078778	417544	2028588	154.51	30.6	398.70
6	Riv6.shp	417259	2065608	422374	2028693	141.72	17.8	249.07
7	Riv7.shp	429724	2062713	422389	2028708	120.38	7.6	33.64
8	Riv8.shp	437299	2066688	432319	2036868	125.37	12.6	341.40
9	Riv9.shp	433444	2055648	432334	2036883	104.55	8.3	100.56
10	Riv10.shp	424594	2052528	432124	2050458	105.75	9.5	95.90
11	Riv11.shp	434704	2045673	432154	2050458	91.70	16.3	304.84
12	Riv12.shp	438859	2032743	432964	2060538	87.45	12.1	91.48
13	Riv13.shp	429979	2036073	432934	2060568	72.95	14.5	195.83
14	Riv14.shp	411364	2039733	429064	2065563	81.55	16.6	214.65
15	Riv15.shp	410584	2025693	429079	2065578	80.01	15.1	183.20
16	Riv16.shp	419929	2030208	434914	2075838	62.35	3.9	41.19
17	Riv17.shp	425674	2026908	434914	2075868	55.11	8.6	101.32
18	Riv18.shp	425509	2013453	429514	2089398	61.31	14.8	171.04
19	Riv19.shp	444664	2014683	429499	2089428	22.48	22.5	430.46

Input data on non-measured parameters

A number of non-measured parameters were used in a model calibration exercise using the Nash–Sutcliffe efficiency as criteria (Moriasi et al. 2007). The similarity pattern was determined from the coefficient of correlation. Parameters that were used for this calibration included the potential canopy interception and relative drought threshold per land-cover type (Table 3.25) and a number of the catchment response parameters (Table 3.26).

Table 3.25 Final input parameter BD/Bdref, potential interception and relative drought

No	Land Cover Type	BD/BDref	Potential Interception (mm day ^{1})	Relative Drought Threshold
1	Bare soil	1.2	1.0	0.3
2	Dry deciduous forest	1.1	4.0	0.5
3	Hill evergreen forest	1.0	4.0	0.4
4	Waterbody	1.3	0.0	1.0
5	Mixed deciduous forest	1.1	4.0	0.5
6	Pine	1.1	4.0	0.4
7	Crop	1.1	1.0	0.7
8	Paddy rice	1.2	1.0	0.9
9	Urban	1.3	0.5	0.0

Model calibration was only carried out across the years for which data were available and no year-specific ad hoc adjustment were made. Model calibration was not pursued beyond "coarse tuning" of round numbers. A key parameter for the dry season recession rate (GWreleaseFracVar) was tuned to the overall pattern in dry periods.

Table 3.26 Final input parameters GenRiver

Acronym	Definition	Dimension [default value]
RainInterceptDripRt (i)	Rain interception Drip Rate	10 mm
RainMaxIntDripDur (i)	Rain interception Drip Duration	0.5 mm
InterceptEffectontrans(i)	Rain Interception Effect on Transpiration	0.3 mm
RainIntensMean	Average rainfall intensity	3 mm/day
RainIntensCoefVar	Coefficient of variation of rainfall intensity	0.5
MaxInfRate (i)	Maximum infiltration capacity per unit i	150 mm day^{-1}
MaxInfSubsoil (i)	Maximum infiltration capacity per unit i	150 mm day^{-1}
PerFracMultiplier (i)	Daily soil water drainage as fraction of groundwater release fraction	0.1
MaxDynGrWatStore (i)	Dynamic groundwater storage capacity	300 mm
GWReleaseFracVar (i)	An option to have a constant groundwater release fraction for each subcatchment or using single value for the whole catchment	0.05
Tortuousity (i)	Stream shape Factor	0.6
Dispersal Factor (i)	Drainage density	0.3
River Velocity (i)	River Flow velocity	0.3 m s^{-1}

3.2.3. Model output

Model performance

Using Nash-Sutcliffe Efficiency (NSE), the performance of GenRiver model was satisfactory to very good for a 15-years simulation (Table 3.27). The model was simulated by using rainfall data from 1 January 1989 to 28 February 2003. We obtained a range value of NSE coefficient of 0.52 to 0.81; coefficient of correlation (r) is more than 0.6 and the biased less than 25%.

The model simulation could capture most of the observed pattern across a 14-year period (Figure 3.17). At a more detailed level, Figure 3.18 compares observed and simulated flows for some years (1991, 1994, 1997 and 2001). The simulations include systematic land-cover change in the various subcatchments.

Table 3.27 Performance of GenRiver based on Nash-Sutcliffe efficiency (NSE) criteria of Moriasi *et al.* (2007)

Year	n	Biased (%)	NSE	r	NSE
1989	365	7.3	0.14	0.6	unsatisfactory
1990	365	50.5	-1.73	0.6	unsatisfactory
1991	365	0.6	0.63	0.8	satisfactory
1992	365	3.8	0.45	0.7	unsatisfactory
1993	365	-13.2	0.58	0.8	satisfactory
1994	365	-6.4	0.52	0.7	satisfactory
1995	365	-14.4	0.75	0.9	good
1996	365	-21.0	0.63	0.8	satisfactory
1997	365	-11.8	0.81	0.9	very good
1998	365	68.5	-0.23	0.9	unsatisfactory
1999	365	8.5	0.63	0.8	satisfactory
2000	365	3.4	0.01	0.7	unsatisfactory
2001	365	29.3	0.52	0.8	satisfactory
2002	365	-64.2	-0.01	0.8	unsatisfactory
2003*	365	260.9	-8.84	-0.1	unsatisfactory

2003 data until 28 February*

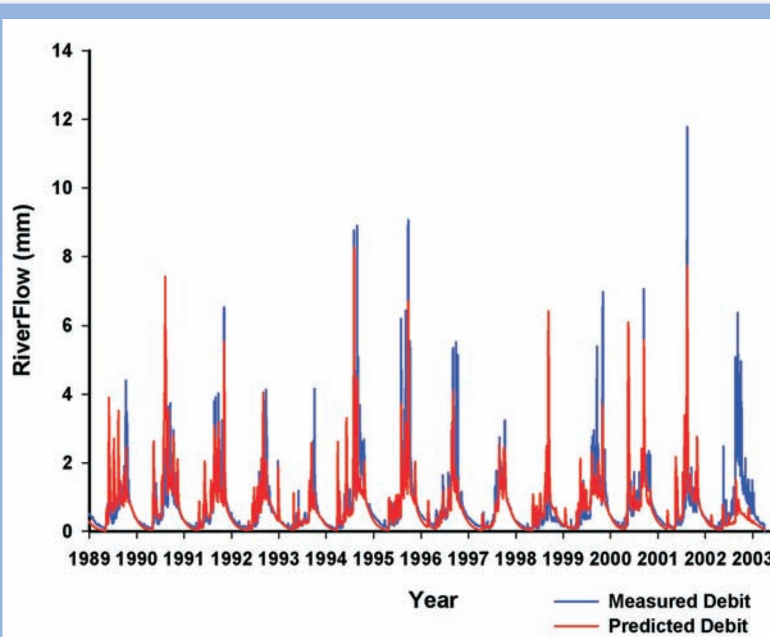

Figure 3.17 Plot of simulation against the observed flow for 1 January 1989–28 February 2003

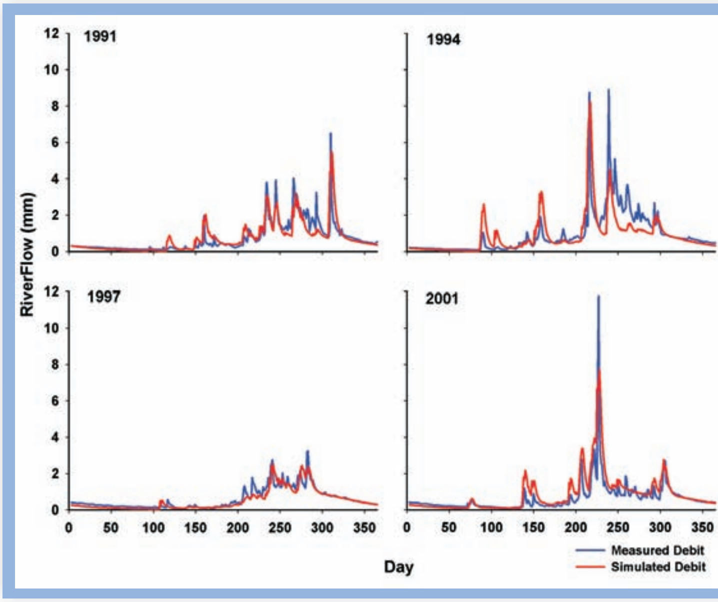

Figure 3.18 Hydrographic simulation: result of land-cover change

While the model after calibration of the ground water release parameter is acceptable for low-flow periods it is less accurate in simulating high flows (Figure 3.19). The simplest "excuse" for this is under-representation of spatially variable rainfall data. After the calibration step the simulation slightly overestimated river flow in the first half of most hydrological years and underestimated it in the second half of many years (but not all).

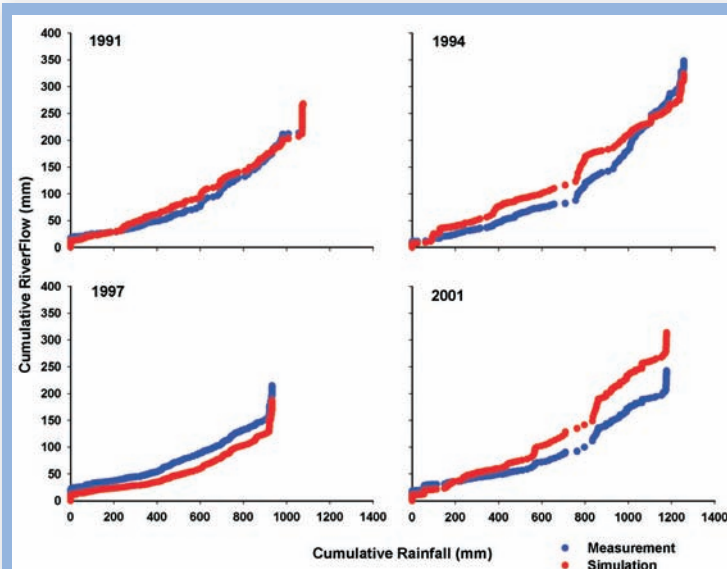

Figure 3.19 Annual cumulative rainfall vs cumulative river flow

Estimated average water balance

The estimated average water balance of Mae Chaem basin in 14 years (excluding the two hydrological years with unsatisfactory results) (Table 3.28) showed the evapotranspiration in the area was about 76% of annual rainfall and that base flow was 12% of annual rainfall. Runoff in the whole catchment area of 3890 km^2 was about 11% of annual rainfall, while with these parameter settings the soil quick flow was negligible.

Table 3.28 Water balance during 10-year simulation (excluding the hydrological years 1998–1999 and 1999–2000)

No	Element	Simulated			Observed		
		Min	Average	Max	Min	Average	Max
1	Precipitation (mm)	641	1027	1360	702	1054	1360
2	Evapotranspiration(mm)	551 (86)	785 (76)	1042 (77)	-	-	-
3	River flow (mm)	113 (18)	243 (24)	357 (26)	121 (17)	260 (25)	363 (27)
	- Runoff (mm)	35 (6)	117 (11)	190 (14)			
	- Soil quick flow (mm)	0 (0)	1 (<1)	2 (<1)			
	- Base Flow (mm)	78 (12)	125 (12)	165 (12			

**Values in parentheses are percentages*

The simulation corresponded with a previous study in Mae Chaem which reported that simulated average annual evapotranspiration and river discharge was 76% and 24% respectively of total rainfall (Thanapakpawin *et al.* 2005).

River flow in Mae Chaem basin was strongly seasonal, the water balance showing average annual evapotranspiration (765 mm) was just slightly lower than the average annual rainfall (1100 mm).

Indicators of watershed function

The watershed function indicators as the effect of year-to-year variations in rainfall show that the total discharge fraction did not vary within the 14-year period (ranging 0.16–0.29). The river flow was quite stable throughout the year (Table 3.29). The buffering capacity (0.81–0.92) and other watershed function indicators tend to be stable except for runoff (overflowfrac). The runoff tends to increase (0.05–0.16) with total discharge (Figure 3.20).

Table 3.29 Average of indicators of watershed functions for Mae Chaem basin for 1992–2002

Indicators	Min	Average	Max
Total Discharge Fraction	0.16	0.24	0.29
Buffering Indicator	0.81	0.85	0.92
Relative Buffering Indicator	0.30	0.39	0.53
Buffering Peak	0.81	0.87	0.94
Highest Month Fraction	1.85	3.01	4.22
OverlFlow Fraction (runoff)	0.05	0.11	0.16
Soil Quick Flow Fraction	0.00	0.00	0.00
Slow Flow Fraction	0.11	0.12	0.13
Lowest Month Fraction	0.04	0.11	0.22

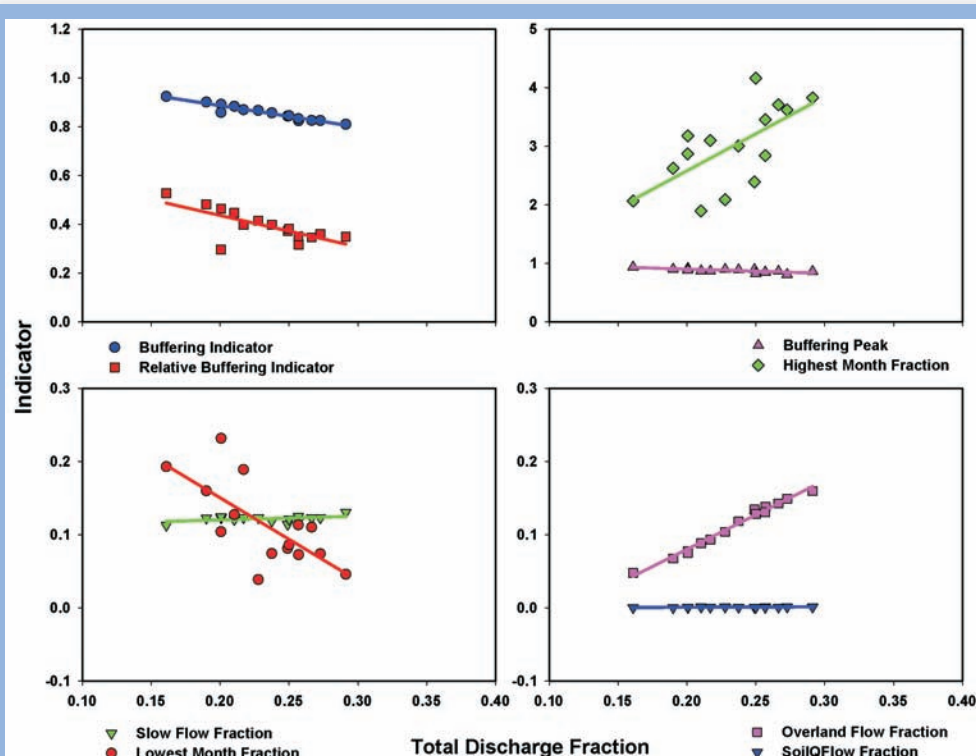

Figure 3.20 Indicators of watershed function of Mae Chaem, expressed in relationship to the total discharge fraction (which is positively correlated with annual rainfall), over a 11-year period

3.2.4. Discussion and conclusions

Using the existing data and current hydrological studies of the Mae Chaem basin to parameterize the input of the GenRiver model, the result of simulation showed more than 55% of the simulation year with satisfactory-to-very good performance (NSE 0.52–0.81).

The water balance in Mae Chaem indicated that around 24% of rainfall flowed into the river, while 76% was used by the vegetation and lost as evaporation. According to the model, 11% of rainfall comes as surface runoff and 12% as ground water flow with negligible amounts of soil quick flow. The second half of the hydrological years had a higher discharge fraction than the first as the landscape became closer to saturation with the relatively high transfer to deep ground water stores. However, the main reason for overland flow remains rainfall intensity exceeding the instantaneous infiltration rates of the soils rather than saturation of the topsoil. This result was in contrast with the simulations for Sumberjaya (Indonesia) where soil quick flow was more common and evapotranspiration was a much smaller fraction of the higher annual rainfall.

The watershed function indicators suggested that variation between years in overland flow has little bearing on other indicators of watershed function, including the dry season flow and buffering indicators. Overall, the watershed does not signs of hydrological degradation.

CHAPTER 4

4. Description of model sectors

4.1. Why a river flow model?

With a short time-span for most observers of river flow it is difficult to distinguish interannual variability of weather from real change in climate and from changes in land cover and soil conditions.

The hydrology of the river basin integrates processes at a range of temporal and spatial scales and the interactions between "input" and "water processing" at patch and river-channel scale are not easily unravelled. Purely empirical (data-driven) models may need only a few parameter to reconstruct a daily hydrograph from rainfall data, but because their parameters cannot "unpack" at the land-use level, such models are not suited for scenario models where the effects of land-cover change (including forest cover) is the main interest (Croke *et al.* 2004).

Spatially explicit models that make use of a basic understanding of the underlying mechanisms tend to require a large number of spatially explicit parameters, more than are normally available. If such models are used for model optimization there may be too many degrees of freedom for improving the model fit and it is hard to decide which among a range of parameterization options to use for subsequent scenario studies (Thanapakpawin *et al.* 2005).

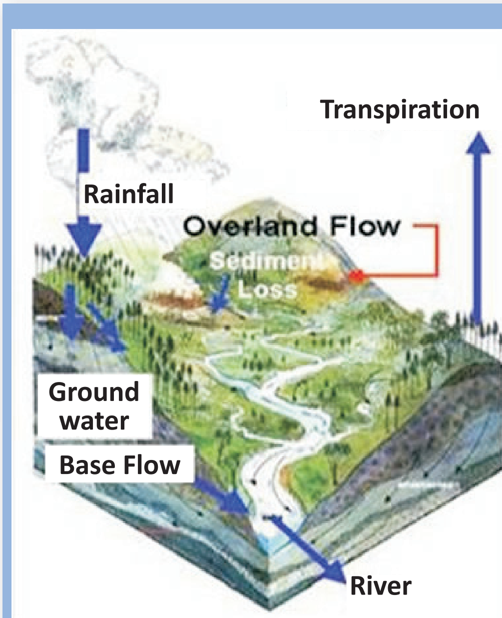

Figure 4.1 The biophysical relations between rainfall, land use in upper catchments and river flow to downstream

The term "watershed functions" is often used in a rather loose way, suggesting that its various aspects (dimensions) change in a similar way when we make comparisons across climatic zones, land forms and human-induced land-cover change. In reality, however, changes in total quantity of water may not be of the same relative magnitude (or even sign) as changes in quality or regularity of flow and a differentiation among the functions is needed. The functionality of various aspects of river flow depends on the perspective, however, and thus may differ between various stakeholders. So, we may want to restrict ourselves to the hydrological consequences of a watershed and leave the value judgements of functions to a later step in the analysis. The three main outcomes of current interest are:

- Quantity or total water yield
- Evenness of flow, which implies high flows in the dry season and an absence of strong peak flows in the wet season
- Quality of water, with respect to its use as drinking water, other domestic uses, industrial use, irrigation or as habitat for fish and other water organisms

The behaviour of streams and rivers in these respects can be seen as the consequence of:

1. Site properties that "come with the territory"

- local rainfall regime (and its temporal autocorrelation or tendency for wet days to follow wet days)
- slope
- soil depth and texture, determining the potential water storage, transport and retention
- underlying landscape and geology that determines potential storage and release of groundwater
- inherent properties of the riverbed

2. Scale

- size of the catchment (upstream of the observer/stakeholder) relative to the spatial autocorrelation of rainfall

3. Land use that directly depends on human activities

- infiltration and supply to groundwater as potentially influenced by soil structure that itself depends on vegetation and land use
- vegetative aspects of the properties of the riverbed (and temporary storage) that dominate pulse transmission
- irrigated agriculture and horticulture based on extractions from rivers

4. Engineering structures

- canalisation of streams and rivers, increasing the rate of drainage
- regulating structures in the river
- impediments to rapid drainage in the form of dams and reservoirs

Where much of the public debate attributes most of the changes in watershed functions to a change in forest cover (deforestation or reforestation), we need tools to account for the interactions of all four aspects mentioned here, to help us in assessing the causality of changes and the opportunities for interventions.

Various approaches exist for modelling watershed functions, ranging from directly data-driven (empirical) approaches to models based on concepts of a water balance, soil physics and hydrology. Models differ by temporal and spatial scale: detailed description of rainfall and infiltration may require a minute (or even seconds) time step, especially on slopes where water will become surface runoff if it cannot infiltrate within seconds of reaching the soil surface. At the other end of the spectrum we may find empirical equations relating annual water yield of a catchment to annual rainfall (or precipitation in climate zones where snowfall and ice rains are significant). For some Indonesian catchments, for example, an empirical equation (Rizaldi Boer pers. comm.) was derived as:

$$Q = 0.94\,P - 1000\ \text{mm year}^{-1}$$

with Q as river flow and P as precipitation both in mm year^{-1}. A tentative interpretation of these coefficients is that 6% of rainfall is lost through interception and direct evaporation from wet leaf surfaces and/or a rainfall-dependent increase in plant transpiration and that the basic value for annual evapotranspiration is 1000 mm year^{-1}. Both these parameters, the interception loss and the evapotranspiration, will vary with the temporal distribution of rainfall and the land-cover type, but the intercept is unlikely to change by more than 50% of the values given (so the intercept is unlikely to be more than 1500 or less than 500 mm year^{-1}), while the slope is probably confined to the range 0.8–1. The simple model may thus be fairly robust, but it is not sensitive to changes in land use or land cover (these could shift the parameters from the indicated values), and cannot be directly downscaled to shorter periods of time (as it does not consider changes in storage terms). More sophisticated models will need to be explicit in the basic value for evapotranspiration of different types of land cover and the degree to which these land covers induce direct evaporative losses.

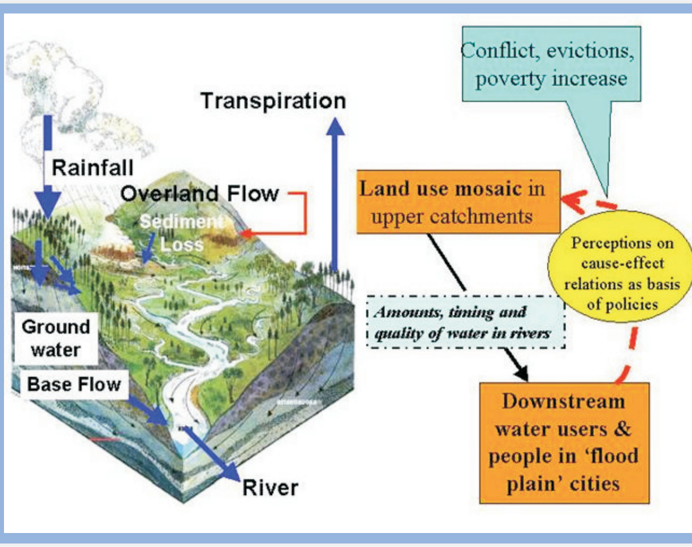

Figure 4.2 The biophysical relations between rainfall, land use in upper catchments and river flow to downstream areas are subject to discussions between downstream and upland people whose perceptions on the cause-effect relations are reflected in policies that may aggravate poverty and conflict

Four classes of land cover can be distinguished for evapotranspiration:

- *open waterbodies*
  where water loss is determined by the relative humidity of the air and the presence of a stagnant boundary layer of air that reduces the transport of water vapour
- *open soil*
  which may have a rate of evaporation similar to open waterbodies when the surface is wet, but where evaporation may rapidly become limited by the rate of transport to the soil surface; soil cover with a litter layer provides a stagnant air zone, further reducing transport opportunities and mixing with the atmosphere
- *seasonally green vegetation*
  most plants are able to provide their leaves (evaporating surfaces) with the amount of water that is needed for evaporation similar to an open water surface, during most of the rainy season; during periodic dry spells, plant transpiration is likely to drop below the value of open water, but stay above that of open soil
- *evergreen vegetation*
  such as evergreen trees (for example, pines, eucalypts, grevillea), irrigated rice paddies or vegetable crops will have a rate of transpiration equal to that of open water or higher if lateral flows of dry air drive the evapotranspiration per unit area to higher levels

If we take for granted that effects of local land use on total annual rainfall are small, the main effect on total water yield of a catchment area is a change in the rate of evapotranspiration, or the return flow of water molecules to the atmosphere. In a simple equation: $Q = P - E - \Delta S$ or the total water yield (surface rivers Qr + subsurface lateral flows Qs + groundwater flows Qg) equals precipitation (rainfall plus snow and ice, which in most parts of the tropics can be ignored) minus evapotranspiration minus the changes in storage terms of water in the catchment. If the timeframe for evaluation is sufficiently long relative to the variability of rainfall (for example, one year for predictable humid climates but multiple years for more erratic drier areas), the ΔS term can be ignored.

To reduce evapotranspiration and thus increase total water yield, do not plant evergreen trees (especially fast growing ones) or irrigate rice paddies or vegetable crops in the dry season.

By expressing the rainfall and river flow in mm year^{-1} we essentially use volume of water per unit area as the basis for calculations; if we consider larger areas, where both rainfall and evapotranspiration vary with space, we will need to make an effort to adjust the average value to maintain validity of the equation. For annual water yield, however, an area-based approach to scaling is valid and values per unit area can be used to estimate values for any scale through multiplication with area. For properties such as “evenness of flow” or probability of flooding, the relation with the scale of consideration is more complex and a greater sensitivity to both the mean value of land-cover fractions as well as the spatial organization of the landscape is probably needed.

If a greater model sensitivity to land-use change is important for the question we try to answer or if we are interested in phenomena operating at shorter time scales than a year, we need to take into account the intermediate processes that determine the access to, and use of, water stored in the soil and the upper groundwater, as well as the rates of transport and temporary storage of water in the river network. The basic framework for a patch or plot-level water balance (Figure 4.3) is well accepted, so the various models differ in the details of the time course of describing canopy interception and throughfall and the way lateral flows over the surface and through the soil are described. As most plot-level studies exclude surface inflows, there is a tendency to focus on surface runoff rather than run-on or net transport.

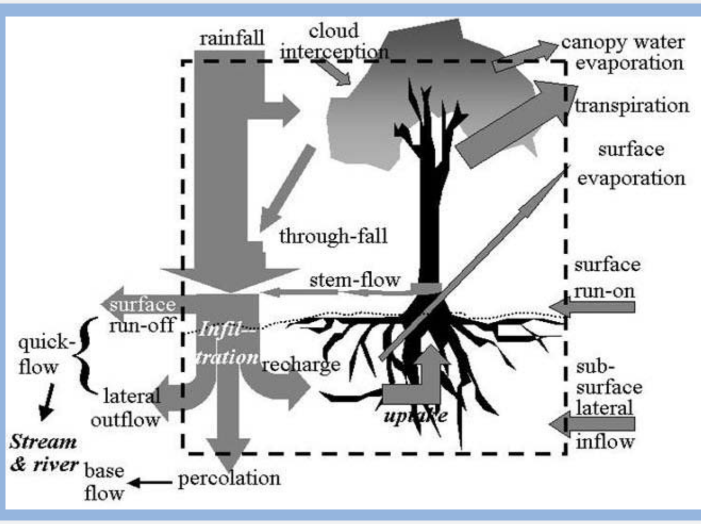

Figure 4.3 The basic framework for a patch or plot level water balance

Table 4.1 Models' concepts of river flow

	Single scale	Spatially explicit, multiple entities at the same scale	Across scale
Empirical, catchment specific	Hydrograph analysis, runoff fraction at plot level, USLE, "Parsimonious" catchment models	Spatial correlation of rainfall, USLE applied to GIS grid data	Nested hydrograph analyses, Sediment delivery ratio
Based on water balance and generic principles of soil physics and hydrology	Plot-level water balance, Catchment-level water yield model	GIS: raster or polygon based	Nested models with explicit scaling rules

A number of existing models address only a single scale, be it a plot or a catchment as a whole (Table 4.1). Other models use a grid-cell approach with interactions between "cells" leading to emergent behaviour at the catchment scale. A third category of models addresses the cross-scale questions in a more direct way by being specific about how properties change temporally and spatially.

4.2. GenRiver Model

The model was initially designed as a "simple" (few parameters) model that still has a link to process-based models and that can be gradually spatially differentiated, as the need arises.

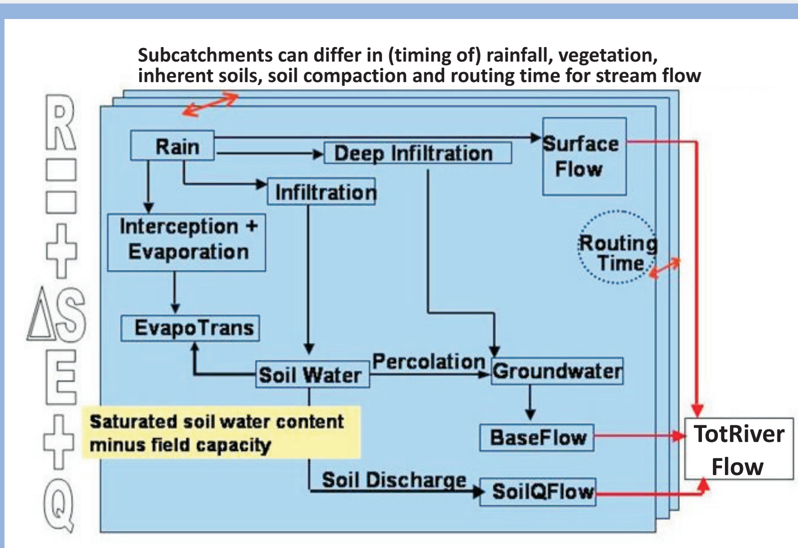

Figure 4.4 Overview of the GenRiver model: the multiple subcatchments that make up the catchment as a whole can differ in basic soil properties, land-cover fractions that affect interception, soil structure (infiltration rate) and seasonal pattern of water use by the vegetation. The subcatchment will also typically differ in "routing time" or in the time it takes the streams and river to reach an observation point

Table 4.2 The overall water balance of the model, summed over space and time

In	Out
P = precipitation (rainfall)	E = Evapotranspiration
- Δs = Changes in soil and groundwater storage	Q = River debit (summed over base flow, soil quick flow and surface quick flow)
- Δr = Changes in the volume of water in streams and rivers	ε= Error (*unaccounted for*) term (difference between all in and out terms)

The core of the model is a patch-level representation of a daily water balance, driven by local rainfall and modified by the land cover and soil properties of the patch. The patch can contribute to three types of stream flow: surface quick flow on the day of the rainfall event, soil quick flow on the next day; and base flow, via the gradual release of groundwater (Figure 4.4).

In the long-term, changes in soil and groundwater storage, as well as changes in the volume of streams and rivers, will be negligible, while the error term should be negligible at all times if the model is correctly implemented.

Many models for river flow, especially for drier areas, focus on the overland flow directly after rainfall (quick flow) but do not account for the "slow flows", that derive from water that infiltrates into the soil but can take a range of pathways, with various residence times, to reach the streams and rivers, depending on land form, geology and extractions along the way. To keep things simple, GenRiver distinguishes only two steps in this: a soil quick flow (or “interflow”) that is considered to reach the streams a day after the rainfall event and a “slow flow” that forms a fraction of the available store of groundwater (leading to an exponential decline of the groundwater store with time and a linear relationship between the logarithm of the discharge and time in the absence of rainfall).

The GenRiver model was made for data-scarce situations and is therefore based on “first principles”, as these may be considered the safest bet for a wide range of applications (acknowledging that directly empirical models may have greater precision within the tested range). The model includes an attempt to relate across spatial scales (Figure 4.5).

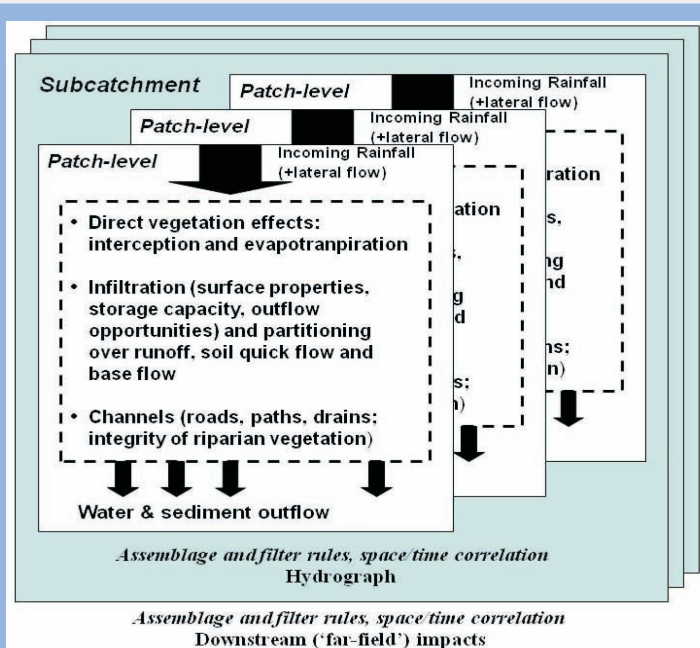

Figure 4.5 Models for watershed functions at catchment scale need to combine explicit rules for effects of land use on interception, infiltration and transport to the stream network at “patch” scale, with assemblage and filter rules that reflect the river network and the changes that this can cause to the overall flow

4.2.1. Two alternative explanations for steady-river flow

Everybody is probably familiar with the “mental model” of a forest as a sponge that receives rainfall and gradually feeds it to the stream. The concept, clearly formulated in the 1920s in Indonesia, but is much older than that, was seriously questioned in the 1930s and internationally in the last two decades (Calder 2002). The validity of the concept is especially questionable for the humid tropics, where the sponge will be continuously wet and not able to absorb much of the incoming rainfall. Yet, the “sponge” concept still leads to specific expectations that only “forest” can play this role. If we accept that some forms of “non-forest” can maintain infiltration rates, the “local buffering” perspective still leads to strong concerns against any land use that reduces the residence time of water in the system, on its way from rainfall to the river.

There is, however, an alternative explanation for even river-flow patterns that receives much less attention: spatial heterogeneity of rainfall. Simply put, if today it rains here and tomorrow there, a river that receives water from both areas may have a fairly steady flow, despite poor buffering in either area (Figure 4.6). If this second model dominates, changes in river flow may be owing to a change in the spatial correlation of rainfall, not to land-use change in any of the subcatchments.

A distinction between these two types of explanation for patterns in river flow is thus essential to evaluate the likely impact of current land-use change in forested areas and the types of interventions that may be effective or not. The relative importance of the two explanations clearly depends on the scale of consideration. In small subcatchments there is hardly any space for the second explanation and the first must dominate.

In areas of several hundreds of square kilometres or at subcontinental scale, the second reason is likely to dominate. So, somewhere at intermediate scale the two may break even. Can we assess where this occurs? Unfortunately, most past research was done in small plots and, when “scaling up”, the possible impact of the second explanation was not recognized. In summarizing data on land-use impacts on river flow (Kiersch and Tognetti 2002), no cases were reported with measurable impacts of land-use change on river flow of areas larger than 100 km^2.

The GenRiver models were first designed to answer this rather specific question: how does spatial variability of rainfall influence the “evenness” of river flow that is often attributed to forests as dominant land cover or “explanation 2”? We first of all need a representation of rainfall with spatial patterns that are intermediate between uncorrelated random and fully coupled. We then need to link this to a model that includes the “sponge” in its essential form so that we can compare the relative importance of both processes. The two tools described here were developed for such a purpose. We will briefly outline the conceptual basis of both, describe the model implementation and parameter sensitivity, and then proceed with the analysis of the relative impacts of land-use change on river flow in catchments with spatially heterogeneous rainfall.

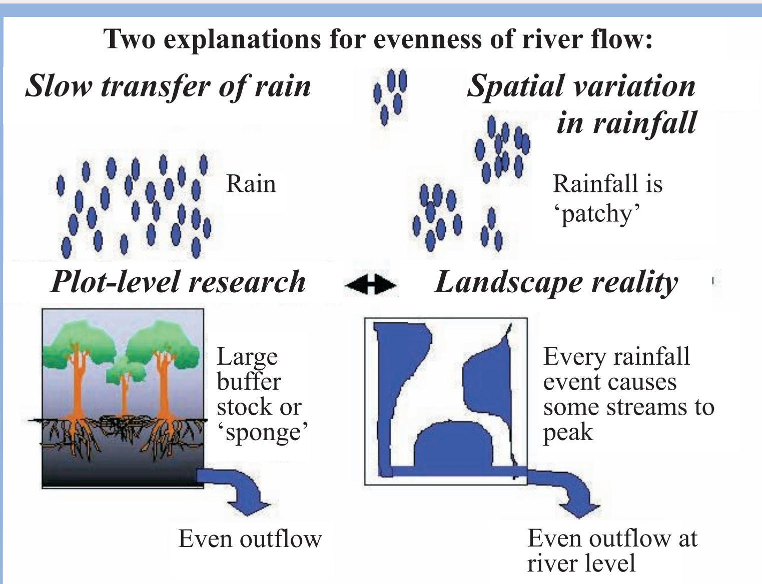

Figure 4.6 Two alternative models for steady river flow: the "sponge" and "patchy rain" versions that are likely to dominate research at plot (left) and landscape (right) levels

Table 4.3 Well-documented impacts of land-use change by basin size (Kiersch and Tognetti 2002); x = Measured impact; - = No well-documented impact

	Impact Type Basin size [km]						
	0.1	1	10	10^2	10^3	10^4	10^5
Thermal regime	x	x	-	-	-	-	-
Pathogens	x	x	x	-	-	-	-
Average flow	x	x	x	x	-	-	-
Peak flow	x	x	x	x	-	-	-
Base flow	x	x	x	x	-	-	-
Groundwater recharge	x	x	x	x	-	-	-
Organic matter	x	x	x	x	-	-	-
Sediment load	x	x	x	x	-	-	-
Nutrients	x	x	x	x	x	-	-
Salinity	x	x	x	x	x	x	x
Pesticides	x	x	x	x	x	x	x
Heavy metals	x	x	x	x	x	x	x

4.2.2. Quantification of "buffering" of river flow by watershed areas

A basic concept in watershed functions is "evenness of river flow", indicating low peak flows and high base flows. The variation in river debit between different rivers, however, is largely due to variation in rainfall and it is no easy task to separate this climatic effect (that we assume to be independent of local land-use change, for the time being at least) from the impacts of land-use change. The following definition of "buffering" can allow us to make this separation.

An efficient way of presenting the input and output of a watershed area in a single graph is to look at the exceedance probabilities for daily rainfall, daily evapotranspiration and daily river flow. If a sufficiently long time period is considered (at least one year), changes in storage in soil, ground water and surface water may be negligible and the areas to the left of the curves for rainfall and evapotranspiration and river flow should be approximately equal. The point of intersection has to have an X-value that equals the mean daily rainfall. The intersection would be at an exceedance probability of 0.5 if rainfall distribution were symmetrical and there would be no dry days, though in reality skewed rainfall distribution plus the fraction of days without rain cause the point of intersection to have a value on the Y-axis that is above 0.5.

In an "asphalted" or urban watershed, the river flow curve may be expected to coincide with the rainfall curve and there is no buffering. In an ideally buffered situation the river flow may be constant and equal to the mean at every day of the year. In between these two extremes we find real watersheds with partial "buffering".

4.2.3. Target properties of the model

The model was developed with the following target properties. The model should be:

- based on solid principles of the plot-level water balance and the way this is influenced by land-use change, through vegetation and changes in soil structure over time, preferably compatible in approach to the WaNuLCAS model that operates at higher spatial resolution of soil zones and layers for mixed cropping and agroforestry situations;
- handling processes at less-than-hourly time scale where infiltration is concerned and at daily time scales for stream and river flow;

- applicable to multiple subcatchments that together form a catchment and that receive rainfall events partially correlated (so in between the assumptions of “homogeneity” and “statistical independence”);
- applicable to any land form and digital elevation model (DEM) at “parameter” level, rather than by modifying model structure;
- able to predict river flow (hydrograph) at multiple points of interest; and
- transparent in structure (assumptions) and easy to operate.

4.3. Description of GenRiver components and processes

A river is treated as a summation of streams, each originating in a subcatchment with its own daily rainfall, yearly land-cover fractions and constant total area and distance to the river outflow (or measurement) point. Interactions between streams in their contribution to the river are considered to be negligible (that is, there is no “backflow” problem). Spatial patterns in daily rainfall events are translated into average daily rainfall in each subcatchment in a separate module. The subcatchment model represents interception, infiltration into soil, rapid percolation into subsoil, surface flow of water and rapid lateral subsurface flow into streams with parameters that can vary between land-cover classes.

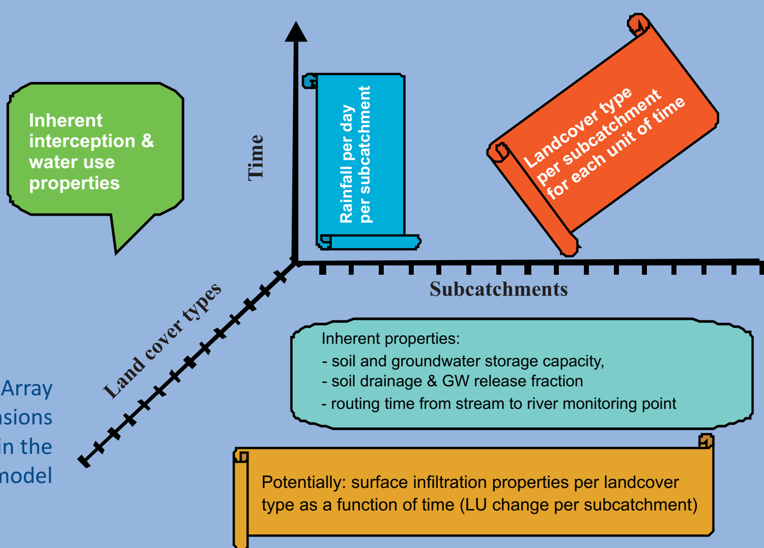

Figure 4.7 Array of dimensions used in the model

GenRiver model consists of several sectors, which are related to one another.

1. Water Balance is the main sector calculating the input, output and storage changes of water in the systems. Components in this sector include rainfall, interception, infiltration, percolation, soil water, surface flow, soil discharge, deep infiltration, ground water area and base flow.
2. Stream Network estimates the flow of water from the river to the final outlet. Components in this sector include total stream inflow, routing time, direct surface flow, delay surface flow, river flow to final outlet.
3. Land Cover generates land-cover data per subcatchment for each year.
4. Subcatchment Parameter stores constant parameters that control the changes of water balance, land cover and stream network.

4.3.1 Water balance

Rainfall

Rainfall at subcatchment level is implemented as daily amounts (I_RainPerDay) from long time records for each subcatchment, stored in an MS Excel spreadsheet (Table 4.4.). The daily rainfall at the subcatchment can be either derived from actual data or from a “random generator” that takes temporal patterns into account (SpatRain Model). The actual data is stored and distributed in “I_DailyRainYear...” parameters (Figure 4.8), while rainfall derived from the SpatRain model is stored in “I_SpatRain...” parameters. Each parameter consists of four years data as this is the maximum that can be loaded into STELLA. This option can be activated by switching “I_UseSpatVarRain?” to 0 (actual data) or 1 (SpatRain data).

Table 4.4 Rainfall input table in MS Excel spreadsheet

Days	Year 1-4	Year 5-8	Year 9-12	Year 13-16	Year 17-20	Year 21-24	Year 25-28	Year 29-32
1	2.84	6.45	27.08	7.54	8.55	6.89	17.21	5.65
2	12.38	10.18	5.05	9.43	6.27	6.65	3.64	15.42
3	9.03	11.42	3.21	10.70	10.19	9.46	9.84	3.46
4	5.08	16.51	1.25	12.11	1.84	0.88	13.99	8.88
5	0.22	16.71	2.10	12.14	6.96	0.73	1.81	3.61
6	9.46	17.87	5.91	23.09	11.97	4.81	1.38	4.46
7	13.47	2.78	2.81	31.64	7.80	3.85	1.32	3.41
...	...	...	...	...	...	...	...	...
...	...	...	...	...	...	...	...	...
1460	0.00	7.34	7.79	4.46	1.76	8.29	0.02	0.00

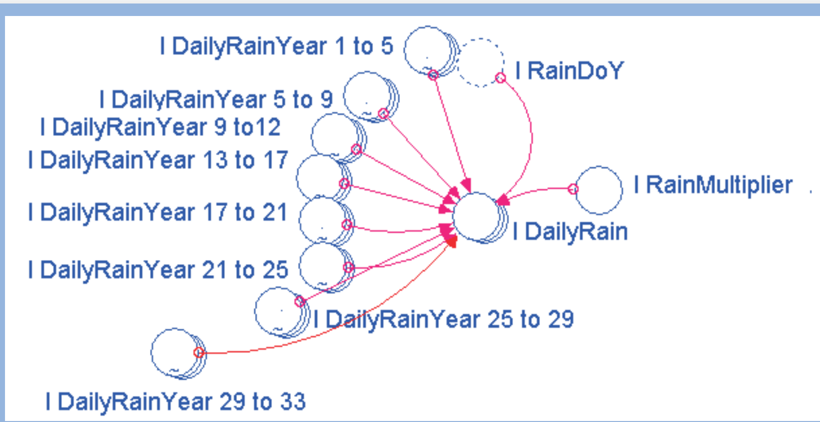

Figure 4.8 Implementation process of daily rainfall at subcatchment level from long-term records

I_RainPerDay = if I_UseSpatVarRain? = 1 then I_SpatRainTime[i] or else I_DailyRain [I]

Rainfall at subcatchment level for each land-cover type (I_ DailyRainAmount) directly calculated proportionally to the area (I_RelArea) and type of each land cover (I_FracVegClassNow).

I_Daily Rain Amount = I_RainPerDay[i] x I_FracVegClassNow[j,i] x I_RelArea[i]

Another parameter that has relation with rainfall is rainfall duration (I_RainDuration). Rain duration is estimated from the daily amount (I_RainPerDay) and rainfall intensity for the given day (mm hour^{-1}) that is derived from a mean value (I_RainIntensMean), a coefficient of variation (I_Rain_IntensCoefVar) and a random number (I_Rain_GeenSeed).

I_RainDuration = (I_RainPerDay[s]/I_Rain_IntensMean) x MIN(MAX (0,1-3 x I_Rain_IntensCoefVar, NORMAL(1,I_Rain_IntensCoefVar,I_Rain_GenSeed+11250)), 1+3 x I_Rain_IntensCoefVar)

Rainfall duration determines the “fraction of time available for infiltration” (I_RainTimeAvForInf), this can also be modified by canopy interception of rainfall followed by the duration of the “dripping” phase (D_RainIntercDelay).

I_RainTimeAvForInf = min(24,I_RainDuration[i]+D_RainIntercDelay[i])

Rainfall will be distributed to each component of water balance, interception-evaporation (D_InterceptEvap), infiltration (D_Infiltration), deep infiltration (D_DeepInfiltration) and runoff (D_SurfaceFlow).

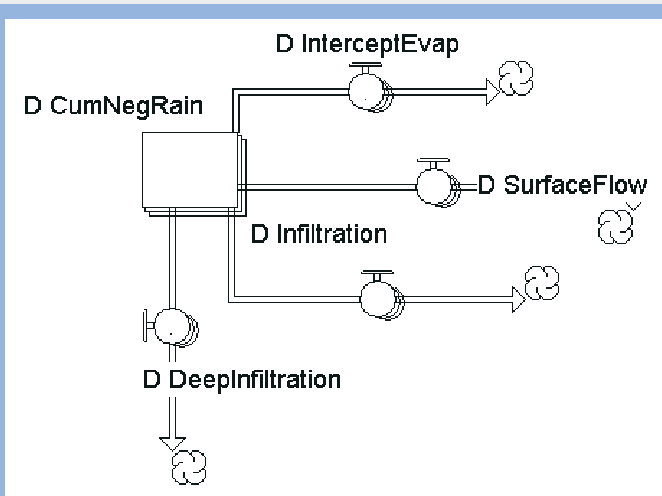

Figure 4.9 Water balance at soil surface level

Interception

Evaporation of intercepted water (D_InterceptEvap) has priority over plant transpiration demand. The proportionality factor for reducing plant transpiration demand on the basis of evaporation of intercepted water can be less than 1 (reflecting the typical time of day of rainfall). The number of interception evaporation value is directly proportional with the storage capacity of land-cover class (I_CanIntercAreaClass) and the daily rain amount (I_DailyRainAmount).

D_InterceptEvap = I_CanIntercAreaClass[j,i] x (1-exp(-I_DailyRainAmount[i,j]/ I_CanIntercAreaClass[j,i]))

The thickness of the water layer that can be stored on leaves and branches (I_InterceptClass) is treated as a constant value for each land-cover type and thus the interception storage capacity is linearly related to leaf area index and it is reflected by its land-cover type (I_FracVegClassnow).

I_CanIntercAreaClass = I_InterceptClass[j] x I_FracVegClassNow[j,i] x I_RelArea[i]

Infiltration

Infiltration is calculated as the minimum of:

- the daily potential infiltration capacity (I_MaxInfArea) times the fraction of a day that is available for infiltration (I_RainTimeAvForInf) (the latter reflects rainfall intensity as well as the local storage capacity of the soil surface);
- the amount that can be held by the soil at saturation (I_SoilSatClass) minus the amount already present (D_SoilWater); and

- the amount of water that can reach the ground water level within a day (I_DailyRainAmount-D_InterceptEvap).

When the surface soil layers are saturated, the rate of outflow will determine the possible rate of inflow on the next day.

D_Infiltration = if L_Lake?[Subcatchement]=1 then 0 else min(min(I_SoilSatClass[j,i]-D_SoilWater[j,i],I_MaxInfArea[j,i] x I_RainTimeAvForInf[i]/24), I_DailyRainAmount[i,j]-D_InterceptEvap[j,i])

If the first constraint is active, the model generates "infiltration limited runoff" or, in the second case, "saturation overland flow".

Infiltration capacity (I_MaxInfArea) driven by maximum infiltration area (I_MaxInf) in patch-water balance of GenRiver: the change of the parameter due to land-cover change over the time was estimated by power equation and soil bulk density relative to the reference bulk density.

I_MaxInfArea = I_MaxInf x I_RelArea[i] x I_FracVegClassNow[j,i] x (0.7/ I_BD_BDRefVegNow[i])I_PowerInfiltRed.

where I_PowerInfiltRed set with range value 3 to 3.5.

The reference bulk density is derived from a pedotransfer function with soil texture (clay and silt) and soil organic matter (SOM) as the main inputs. The BD/BDref ratio depends on land cover, with default values of 0.7 for forest soil, 1 for well-managed agricultural soil and 1.3 for compacted and degraded soil (Van Noordwijk et al 2002). Generic estimation of bulk density reference per soil type is:

If ((Clay+silt)>50 then:

BDref1 = 1 / (1.984 + 0.01841 x (SOM) + 0.032 x 1 + 0.00003576 x (Clay + Silt)2 + 67.5 / 290 + 0.424 x LN(290))

if ((Clay+Silt)<50 then:

BDref2=1 / (0.603 + 0.003975 x Clay + 0.00207 x SOM x SOM + 0.01781 x LN(SOM)))

Deep infiltration

The amount of deep infiltration is calculated as the minimum of:

- the soil saturation (I_SoilSatClass), soil water (D_SoilWater), infiltration of subsurface (D_Infiltration), rainfall amount (I_DailyRainAmount);
- the amount of infiltration of subsurface (I_MaxInfSubSAreaClass); and
- unfilled area of ground water (I_MaxDynGWArea).

D_DeepInfiltration = min(min(min(ARRAYSUM(I_MaxInfArea[*,i]) x I_RainTimeAvForInf[i]/24-ARRAYSUM(I_SoilSatClass[*,i])+ARRAYSUM(D_SoilWater[*,i]),ARRAYSUM(I_MaxInfSubSAreaClass[*,i])),ARRAYSUM(I_DailyRainAmount[i,*])-ARRAYSUM(D_InterceptEvap[*,i])-ARRAYSUM(D_Infiltration[*,i])),I_MaxDynGWArea[i]-D_GWArea[i])

Surface flow

When the net rainfall (rainfall minus interception-evaporation (D_InterceptEvap)) exceeds the infiltration capacity of the soil (D_Infiltration and D_DeepInfiltration) then it becomes surface flow (D_SurfaceFlow).

D_SurfaceFlow = if L_Lake?[i]=1 then ARRAYSUM(I_DailyRainAmount[i,*]) else ARRAYSUM(I_DailyRainAmount[i,*])-ARRAYSUM(D_InterceptEvap[*,i])-ARRAYSUM(D_Infiltration[*,i])-D_DeepInfiltration[i]

Soil water

During a rain event the soil may become saturated, but within one day it is supposed to drain to "field capacity" (with an operational definition of the soil water content 24 hours after a heavy rainfall event). The difference between saturation and field capacity can be either:

- used for transpiration (but canopy intercepted rainfall takes priority to meet the demand) (D_ActEvapTransp);
- drained to the groundwater reserve, calculated as the minimum of the amount that can be transported downwards and the fraction of soil water that will drain on any given day (D_Percolation); or
- drained to rivers as "soil quick flow": any water left above field capacity by the two preceding processes (D_SoilDischarge).

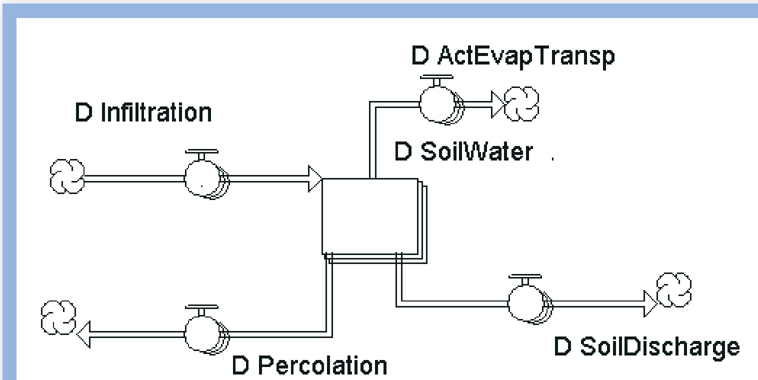

Figure 4.10
The soil water dynamic

After a rain event, the soil starts to drain and will reach field capacity after one day (or, depending on parameters, 1–3 days). The water held between saturation and field capacity is distributed in the order of transpiration, drainage to the ground water reserve or drainage to the rivers as "soil quick flow" (van Noordwijk *et al*. 2003). The soil water retention curve (saturation, field capacity, wilting point) is estimated based on pedotransfer functions using the soil type to indicate the soil texture. The groundwater was driven by the "differential storage" in "active groundwater" and the groundwater release fraction, which represents the recession phase of actual river flow during periods without rainfall.

Actual evapotranspiration

The amount of actual evapotranspiration is proportionally changed by potential evapotranspiration (I_PotEvapTransp), available soil water (D_RelWaterAv) and transpiration of intercepted water (I_InterceptEffectonTransp x D_InterceptEvap).

D_ActEvapTransp = (I_PotEvapTransp[j,i]-I_InterceptEffectonTransp x D_InterceptEvap[j,i]) x D_RelWaterAv[j,i]

Percolation

The amount of percolation is calculated as the minimum of:

- Maximum infiltration of subsurface area (I_MaxInfSubSAreaClass)
- Soil water which can percolate into ground water (D_SoilWater x I_PercFracMultiplier x I_GWRelFrac)
- Unfilled area of ground water (I_MaxDynGWArea-D_GWArea)

D_Percolation = min(I_MaxInfSubSAreaClass[j,i], min(D_SoilWater[j,i] x I_PercFracMultiplier x I_GWRelFrac[i],I_MaxDynGWArea[i]-D_GWArea[i]))-D_IrrigEfficiency[i] x D_Irrigation[i,j] else - D_IrrigEfficiency[i] x D_Irrigation[i,j]

Subsurface flow or soil discharge

Unused soil water by plants has potential to become subsurface flow or soil discharge (D_SoilWater-I_AvailWaterClass). The actual soil discharge depends on how the fraction of soil discharge is initialized (D_SoilQFlowRelFrac).

D_SoilDischarge = D_SoilQflowRelFrac[i] x (D_SoilWater[j,i]-I_AvailWaterClass[j,i])

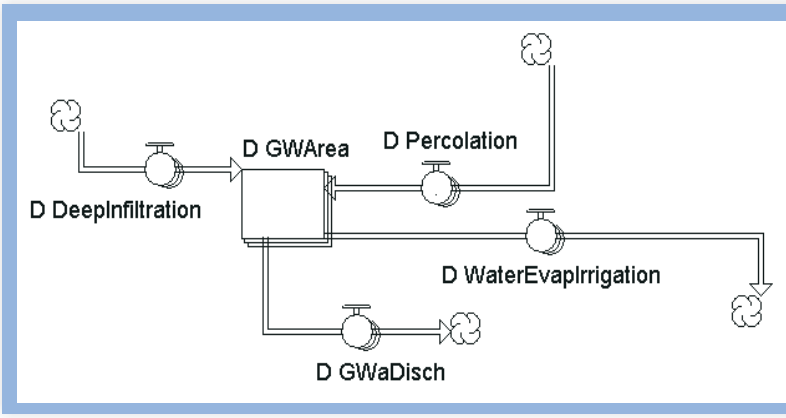

Figure 4.11 Water balance in ground water

Ground water

Percolation and deep infiltration are the source of ground water. The ground water then will be used for irrigation and base flow. Figure 4.11 shows the flows to and from the ground water.

Irrigation

The amount of ground water used for irrigation is controlled by a number of input parameters: utilization fraction of ground water (D_GW_Utilization), relative water available (D_RelWaterAv), irrigation efficiency (D_IrrgEfficiency) and potential evapotranspiration (I_PotEvapTransp).

D_WaterEvapIrrigation = D_Irrigation[i,j] x (1-D_IrrigEfficiency[i])D_Irrigation = min(D_GWArea[i] x D_GWUseFacility?[i,j] x D_GW_Utilization_fraction[i] x (1-D_RelWaterAv[j,i])/D_IrrigEfficiency[i],I_PotEvapTransp[j,i])

Base flow

The portion of stream flow that comes from ground water (D_GWaDisc) depends on how the fraction of released ground water (I_GWRelFrac) is initialized.

D_GWaDisc = D_GWArea[i] x I_GWRelFrac[i]

4.3.2 Stream network

Total stream flow

A river in the model is treated as the sum of streams, each originating in a subcatchment with its own daily rainfall, land-cover fraction, total area and distance to the outlet of the river. These streams are all streams that are listed in the previous section (surface flow, sub-surface flow and base flow). They are included the river and become total stream flow (D_TotalStreamInFlow).

D_TotalStreamInFlow = (D_SurfaceFlow[i]+D_GWaDisch[i] x (1-D_FracGWtoLake[i])+ARRAYSUM(D_SoilDischarge[*,i]))+D_SubCResOutflow[i] x (1-I_DaminThisStream?[i])

Routing time

After entering the river, the streams will flow from subcatchment centre to observation point. Routing time controls the flow of water from subcatchment centre to final outlet. Some input parameters controlling this routing time are distance from the centre of subcatchment to final outlet, velocity and tortuosity.

D_RoutingTime = I_RoutingDistance[i,ObsPoint]/(I_RivFlowTimeNow[i] x I_RoutVeloc_m_per_s x 3.6 x 24 x I_Tortuosity)

There are two types of routing time:

1. If the value of routing time is between 0–1 then the water enters the final outlet on the same day. The amount of direct river flow (D_RivLakeSameDay) depends on the parameter's fraction release value (I_ReleaseFrac).

D_RivLakeSameDay = if D_RoutingTime[i,ObsPoint]>=0 and D_RoutingTime[i,ObsPoint]<1 then D_TotalStreamInflow[i,ObsPoint] x (I_ReleaseFrac[i,ObsPoint]) else 0

2. If the value of routing time is more than 1 then the flow is delayed before entering the final outlet.

4.3.3 Land cover

The land-cover sector generates the proportion of land cover for each year in each subcatchment. Linear interpolation is a method used to generate land cover. Time series of land-cover data with certain year gaps is needed.

There are eleven types of land cover and four time-series data (start simulation, first transition, second transition and end transition) as a default provided by the GenRiver model. Fraction of land-cover change for each year is a result of interpolation. Figure 4.12 and the equation below shows the calculations for interpolation of fraction of land cover for each year in each subcatchment.

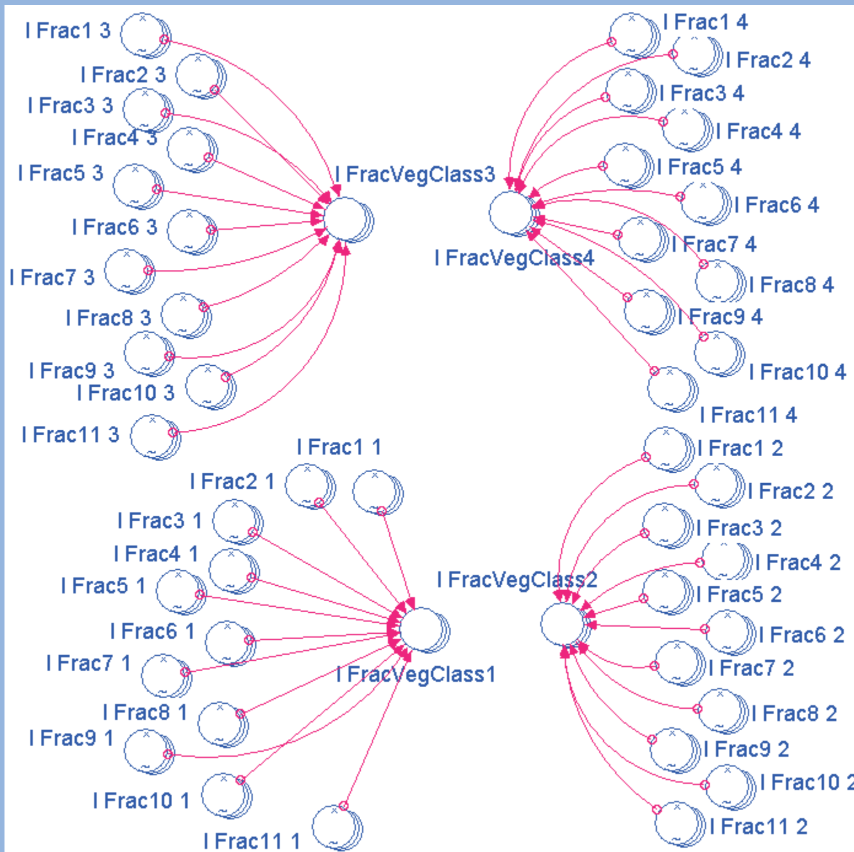

Figure 4.12 Interpolation of land-cover fraction inside GenRiver: Number 1, 2, ..., 11 on I_Frac1_1 1, I_Frac2_1 1, ..., I_Frac11_4, the first number = land-cover type, the second number = the transition year. I_FracVegClass1, I_FracVegClass2, I_FracVegClass3 and I_FracVegClass4 is land-cover fraction for start simulation, first transition, second transition and end transition.

I_FracVegClassNow = if I_RelArea[i]>0 then
(if I_Flag1 = 1 then (I_FracVegClass1[j,i]+((I_FracVegClass2[j,i]-I_FracVegClass1[j,i]) x (int((I_Simulation_Time)/365)-I_InputDataYears[Start])/(I_InputDataYears[Trans1]-I_InputDataYears[Start]))/ARRAYSUM(I_FracVegClass1[*,i])) else
if I_Flag2 = 1 then (I_FracVegClass2[j,i]+((I_FracVegClass3[j,i]-I_FracVegClass2[j,i]) x (int((I_Simulation_Time)/365)-I_InputDataYears[Trans1])/(I_InputDataYears[Trans2]-I_InputDataYears[Trans1]))/ARRAYSUM(I_FracVegClass2[*,i])) else
(I_FracVegClass3[j,i]+((I_FracVegClass4[j,i]-I_FracVegClass3[j,i]) x (int((I_Simulation_Time)/365)-I_InputDataYears[Trans2])/(I_InputDataYears[End]-I_InputDataYears[Trans2]))/ARRAYSUM(I_FracVegClass3[*,i]))) else 0

Other parameters that are also used for interpolation method are water availability for plant (I_AvailWatClassNow), permanent wilting point (I_PWPSub), bulk density (I_BD_BDRefVegNow), a difference value between saturation water storage capacity and field capacity of the soil (I_SoilSatminFCSubNow), ratio of time arrival of river flow (I_RivFlowTimeNow), ground water release fraction (I_GWRelFracNow) and dynamic groundwater storage capacity (I_MaxDynGWSubNow).

4.3.4 Subcatchment parameter

This sector provides a number of constant parameters to fill in unavailable data. The parameters are ground water release fraction (I_GWRelFrac), actual maximum ground water dynamic (I_MaxDynGWat), soil saturation class (I_SoilSatClass), maximum infiltration area (I_MaxInfArea), maximum infiltration sub surface area (I_MaxInfSubSAreaClass) and potential evapotranspiration (I_PotEvapTransp).

CHAPTER 5

5. Flow Persistence and the FlowPer model

5.1. Background: temporal autocorrelation of river flow

Models of river flow, even relatively simple ones such as GenRiver, are over-parameterized relative to the information that we can use to check the statistical validity of the model. There are multiple ways of achieving a similar level of "model fit" between measured and predicted river flow patterns, and the fit obtained may thus be right for the wrong reasons. Using the validated model outside of the calibration range may then be as risky as using a simple regression line. In testing the lack of fit of a model we can benefit from having a null-model: a model that takes basic properties of the data into account, without specific hypotheses about the way rainfall translates into river flow.

In the analysis of watershed functions, we deal with complex factors that influence processes and patterns in the landscape that ultimately translate a temporal pattern of rainfall into a temporal pattern of stream flow, which aggregates up to a river. Downstream stakeholders start from what they want to see ("perfectly regular flow of clean water") and observe a pattern of stream and river flow that doesn't match their expectations. They search for interventions in the "anthropogenic" groups of causes (deforestation, land degradation), but need to understand the potential reach of such interventions, given the geological and climatic background. In the absence of knowledge of what happens upstream, an observer of river flow can deduce a fair amount of information from a time series of river flow data (Table 5.1).

The FlowPer model is focused on that. It can serve two functions: 1) summarize the key parameters that downstream stakeholders can observe on the flow pattern, for example, as a basis for conditional rewards for providing environmental services; and 2) serve as a parsimonious (parameter-sparse) "null model" that allows quantification of the increments in model prediction that is achieved with spatially explicit models (with parameterization first rather than parameter tuning to the data).

5.2. FlowPer model overview

The FlowPer.xls model provides a parsimonious null-model that is based on temporal autocorrelation or an empirical "flow persistence" in the river flow data. The basic form is a recursive relationship between river flow Q on subsequent days:

$$Q_{t+1} = F_p\, Q_t + Q_{add}$$

where Q_t and Q_{t+1} represent the river flow on subsequent days, F_p is the flow persistence factor ([0< F_p <1]) and Q_{add} is a random variate that reflects inputs from recent rainfall.

Q_{add} and F_p are related, as $\sum Q_{add\,i} = (1 - F_p) \sum Q$. Thus, if $F_p = 1$, $Q_{add} = 0$ and river flow is constant, regardless of rainfall (the ideally buffered system). If $F_p = 0$ there is no relation between river flow on subsequent days and the river is extremely "flashy", alternating between high and low flows without temporal predictability within the frequency distribution of Q_{add}.

The term $Q_{add,i}$ can be described as a statistical distribution with a probability of a non-zero value, a mean and a measure of variance, plus two parameters that describe a seasonal pattern (peak and shape of the distribution, for example, Weibull). This makes for five parameters for $Q_{add,i}$ (and six for the whole model) that are derived from the data. It leaves many degrees of freedom for more specific models that, for example, make use of measured rainfall.

If we partition the total flow Q_{tot} into water flow by three pathways (surface runoff, interflow and ground water flow), we can obtain $Q_{tot} = Q_{runoff} + Q_{interflow} + Q_{gwflow}$. Each type of flow pathway will typically have a different flow persistence: $F_{p,runoff}$, $F_{p,interflow}$ and $F_{p,gwflow}$, respectively.

$$Q_{tot,t+1} = (F_{p,runoff}(Q_{runoff,t}/Q_{tot,t})F_{p,interflow}(Q_{interflow,t}/Q_{tot,t}) + F_{p,gwflow}\,(Q_{gwflow,t}/Q_{tot,t}))Q_{tot,t} + Q_{add,t}$$

As we can expect values for $F_{p,runoff}$, $F_{p,interflow}$ and $F_{p,gwflow}$ of about 0, 0.5 and close to 1, respectively, we can interpret the relative contributions of the three flow pathways from the overall F_p value.

In a more detailed model, the daily value of F_p will shift according to the predicted contributions of the three types of flow, rather than being a constant. Together with the way $Q_{add,i}$ relates to rainfall, this gives space for improved model fits.

Part of the "flow persistence" may in fact derive from "rainfall persistence", or the increased probability of daily rainfall after a rainy day, and/or from the increased probability of dry days to follow dry days, even after a monthly pattern ion rainfall is accounted for.

Table 5.1 Multiple influences on process and pattern of river flow and the downstream perceptions of "ecosystem services" (modified from van Noordwijk *et al.* 2006)

Influence	Process and pattern		Resultant river and stream flow	Downstream 'ecosystem service'
Geology Climate Land Use Engineering	Substrate, slope, channels, lakes Soil formation vs erosion, soil depth Rainfall (P): seasonal pattern in quantity, intensity Snowmelt Evapotranspiration (E) Vegetation Modified soil porosity and surface infiltration Nutrient flows, contaminants Soil movement (landslides, erosion, deposition) Surface and/or subsoil drainage Filter functions for nutrients and soil particles Release from/ retention of water in the landscape	Spatially distributed water balance models + routing function	Space-time pattern of stream flow and its water quality water balance: $Q = P - E + \Delta S$ $Q = Q_{GW}+Q_{LF}+Q_{OF}$ (streamflow is based on: groundwater, subsurface lateral flow and overland flow) $Q_t = f_p\ Q_{t-1} + Q_{add}$ $Q_{add} = F(P, E, f_p)$ $f_p = (f_{pGW}Q_{GW}+f_{pLF}\ Q_{LF}+ f_{pOF}\ Q_{OF})/Q$ $MeanQ_{add}=(1-f_p)MeanQ$ for $f_p = 1$, $Q_{add} = 0$ for $fp=0, E(Q_{add})=E(Q)$	Total quantity of water available for downstream use Seasonal pattern of water availability (esp. low flow season) Buffering of peak flows ('flooding risk') and daily 'flow persistence' Water quality in relation to different types of water use Support for aquatic & wetland ecosystems and their productivity Risks of soil mass movement; undesirable sedimentation Nutrient loading and soil (fertility) transfer
Potential feedback on 'anthropogenic' causes	Space-time process-based model of separating the multiple causes and effects		Heuristic, parsimonious 'null-model' based on flow pattern only	LEK/PEK synthesis on expectations & explanations

Institutional for feedback (carrots, sticks and sermons)

5.3. Background of the FlowPer algorithm

Behind the scenes, the FlowPer spreadsheet uses a relatively simple algorithm to find an optimum value for any given data set. It tries out many test-F_p values and uses these to calculate daily value of Q_{add}-estimate from Q_t and Q_{t+1} (Figure 5.1). The larger the value of test-F_p the smaller the mean value of Q_{add}-estimate, as can be seen from the equation (Q_{add}-estimate = Q_{t+1} – test-F_p Q_t). Increasing test-F_p, however, also increases F_p the fraction of daily Q_{add}-estimates that is negative. Negative values may derive from measurement error, but are not consistent with the biophysical model. As in practice, however, data are noisy and a certain fraction of negative Q_{add}-estimates has to be accepted. The algorithm FlowPer uses minimizes the standard deviation (and thus the variance) of Q_{add}-estimates. It thus balances between the decrease in high Q_{add}-estimates and the increase in negative Q_{add}-estimates in the lower range. The F_p value that minimizes the standard deviation of Q_{add}-estimates is found by fitting a quadratic equation through the F_p versus SD(Q_{add}-estimates) relationship.

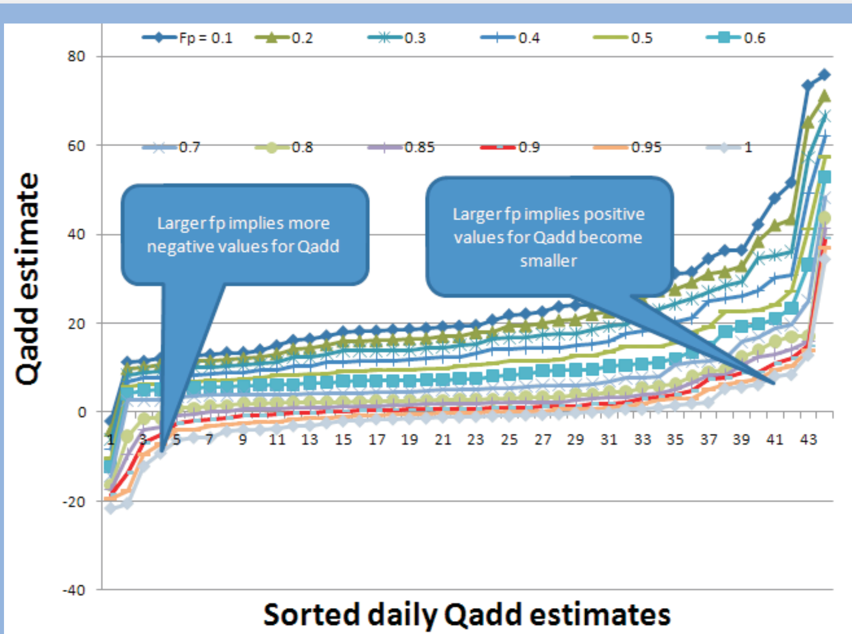

Figure 5.1 Effect of changing the test-F_p value on the frequency distribution of Q_{add}–estimates, showing the decrease of mean and increase of the fraction of negative Q_{add}– estimates with increase in test-F_p value; the algorithm selects the test-F_p value that minimizes the standard deviation of the Q_{add} –estimates frequency distributions

A simple consistency test on the algorithm can be derived from two ways of doubling the mean Q value: 1) adding the mean-Q to all daily Q values; and 2) doubling all daily Q values. The first is expected to increase F_p; the second approach should not. As the data in Table 5.2 show, doubling daily flow data doubles all standard deviations and thus does not affect the F_p that minimizes the standard deviation, while the effect of addition of the mean value depends on the F_p value and thus modifies the F_p estimate derived by the algorithm.

Table 5.2 Standard deviation of the Q_{add}-estimate distributions for a range of Test-F_p values on a data set labelled "Standard" and two data sets that achieve a doubling of mean flow, either through addition of the mean value (A) or through doubling of individual

Test F_p	0.9	0.91	0.92	0.93	0.94	0.95	0.96	0.97	0.98	0.99
Standard	5.654	5.631	5.614	5.603	5.597	5.596	5.602	5.613	5.630	5.652
A. Standard +Mean	7.515	7.439	7.374	7.321	7.280	7.251	7.235	7.231	7.241	7.262
B. Doubling all values	11.308	11.263	11.228	11.205	11.193	11.193	11.204	11.226	11.260	11.304
A/Standard	1.329	1.321	1.313	1.307	1.301	1.296	1.292	1.288	1.286	1.285
B/Standard	2	2	2	2	2	2	2	2	2	2

5.4. Starting and running the FlowPer model

5.4.1. Input parameterization

FlowPer model in the MS Excel file is organized into seven sheets, labeled: "READ ME", "DebitData", "FlowPerModel", "Calculation", "Graphics", "QAddon", "FP", and "Shape and TimeMax" (Figure 5.2).

The only input required is a (partial) time series of daily river flow data, to be entered in the "DebitData" sheet, as in GenRiver.xls. Once river flow data have passed minimum quality checks, we can use them to parameterize the FlowPer model, especially the F_p parameter. The "FlowPerModel" sheet (Figure 5.3) then provides options to run the model for each year that data are available and derive four auxiliary parameters to run FlowPer model (Table 5.3). The four auxiliary parameters are flow persistence ("FP" sheet), the mean random variate that reflects inputs from recent rainfall ("QAddon" sheet) and two parameters that describe a seasonal pattern, peak and shape of the

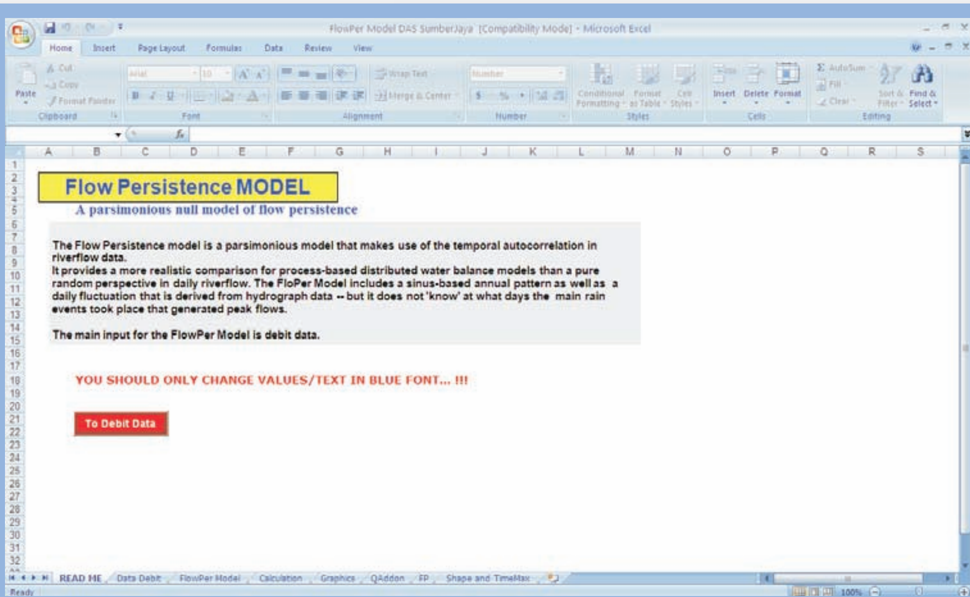

Figure 5.2 The main interface of the FlowPer Model

distribution ("Shape and TimeMax" sheet). The only parameter based on trial and fit is coefficient variation of measurement noise.

5.4.2. Running the model

Once you open the FlowPer model and enter the river flow data on the "DebitData" sheet, click the "FlowPerModel" button and you will see something like Figure 5.3. Table 5.3 presents the location of each input parameter in the MS Excel file.

1. Change the starting year to begin the simulation as entered in "DebitData" sheet.
2. Type year of simulation in the year column to look at the type of fit obtained then simply click "RUN" button.
3. Once the run has finished, copy predicted value of flow persistence (F_p) and random variate of rainfall (Q_{add}) into table of input F_p & Q_{add}.
4. Click "RUN" again until you obtain a fit result by comparing the summary of predicted value and observation value in column D25 and D26.

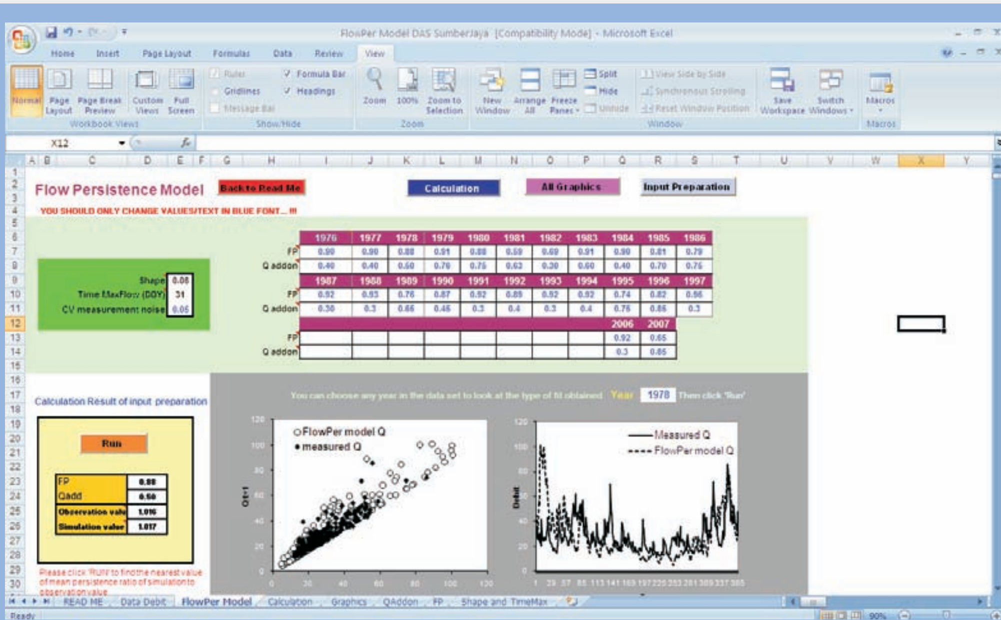

Figure 5.3 The interface of the FlowPer model

Table 5.3 Input parameters of the FlowPer model

Input Parameters	Location in Excel "FlowPer Model" sheet	Note
Start year	I6	Starting year to begin the simulation as entered in "DebitData" sheet.
Year	R17	Year in the data set to look at the type of fit obtained.
Predicted value of F_P & Q_{add}	D23 – D24	Predicted value of flow persistence and random variate of rainfall.
Input F_P & Q_{add}	I7 – S7; I8 – S8; I10 – S10; I11 – S11;I13 – S13; I14 – S14	Input value of flow persistence and random variate of rainfall to be entered as predicted value.
Shape	E9	
Time Maximum Flow	E10	
CV measurement noise	E11	

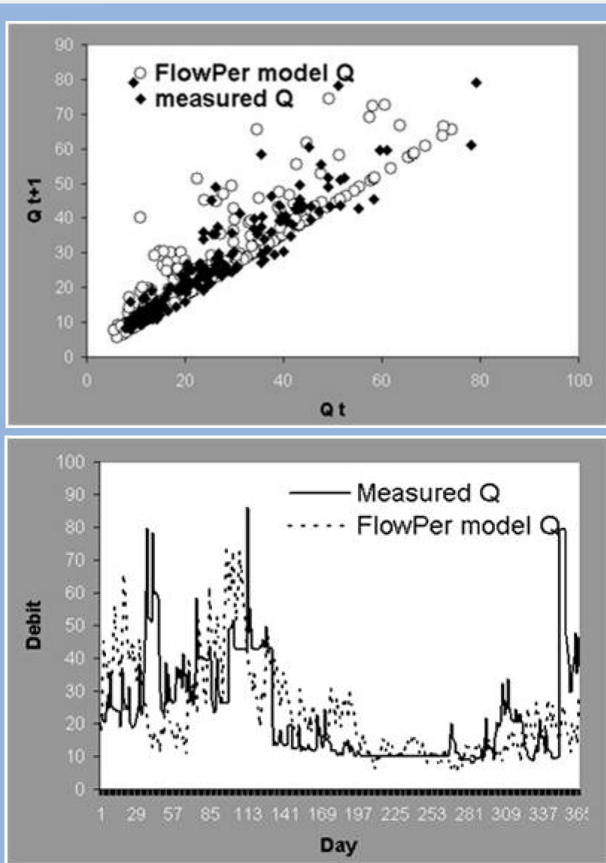

Figure 5.4 Example of the type of "fit" that can be achieved for the six-parameter FlowPer model

5.4.3. FlowPer model output

There are two types of FlowPer model output: flow persistence value and predicted daily river flow. The predicted daily river flow is presented in graph and table forms. There are two types of graph that present the predicted daily river flow (Figure 5.4).

The flow persistence value can be considered as input and output. As input, the F_p is used to generate the predicted daily river flow, while as an output, the F_p is a indicator value of watershed condition that ranges 0–1. If F_p = 0, then there is no relation between river flow on subsequent days and the river is extremely "flashy", alternating between high and low flows without temporal predictability within the frequency distribution of Q_{add}.

5.5. Case Study: Jangkok sub-watershed, Lombok, Indonesia

The total area of Sesaot forest is 5950 ha. It is upstream of the Jangkok sub-watershed, West Lombok (Figure 5.5). Agroforestry is the major land cover, serving economic and ecological functions. The Jangkok sub-watershed is categorized as a priority watershed in local plans (Rencana Pembangunan Jangka Menengah /RPJM) of the Forestry Department, since the area is a source of water for people living in western and central Lombok and the city of Maratam.

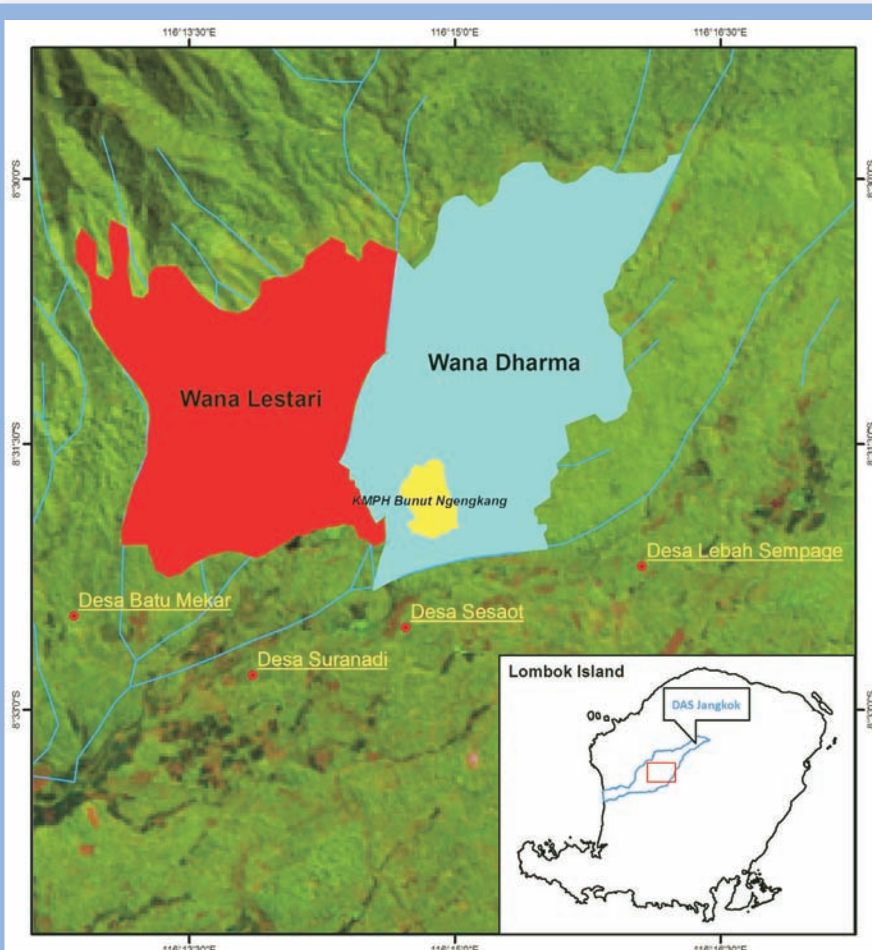

Figure 5.5. Jangkok sub-watershed

Buffer capacity of the sub-watershed was analyzed using the FlowPer model. The flow persistence values tend to increase with an average value of 0.85, reflecting good watershed conditions. The lowest value was found for the 2001 data, at a time widespread (illegal) logging was associated with high flow during wet season and low flow during dry season. The Flow Persistence parameter is a good candidate for a performance measure.

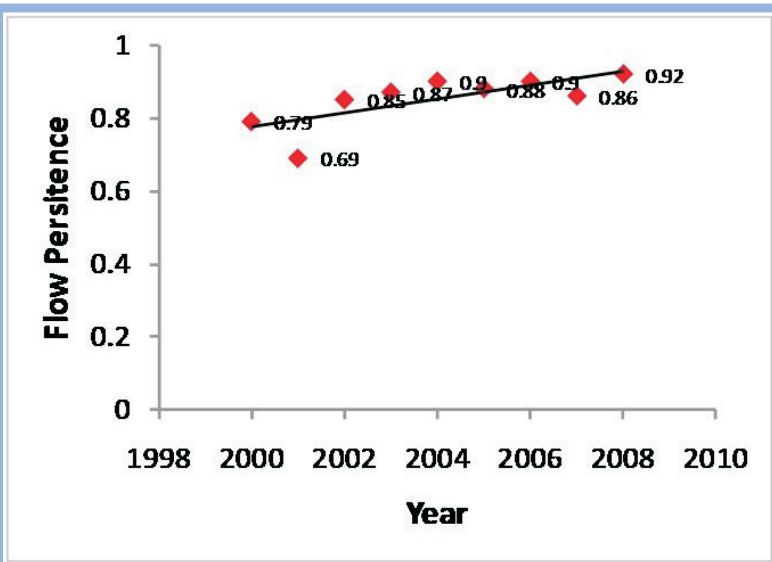

Figure 5.6 Flow persistence value of Jangkok sub-watershed

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APPENDICES

Appendix 1. List of Input Parameters

Abbreviations used in parameter names

No	Acronym	Definition
1.	C	Cattle
2.	D	Dynamic
3.	G	Grass
4.	I	Input/Initialization
5.	L	Lake
6.	O	Output
7.	S	Soil

No	Acronym	Definition	Dimension	Range Value [default value]	Input Section (link location in Excel file)
1.	C_CattleSale	Sale Factor Rate number of Cattle	dimensionless	(0)	Input Section/Cattle & Grass
2.	C_DailyIntake	The daily factor of	dimensionless	(1)	Input Section/Cattle & Grass
3.	C_DailyTrampFac	Daily soil tramping factor	dimensionless	(1)	Input Section/Cattle & Grass
4.	D_FeedingIntoLake?	The option to determine the contribution of river flow per subcatchment to lake. 1 = yes, 0 = no	dimensionless	0 or 1 (1)	Model Sector/I_LandCover
5.	D_SubCResUseFrac	Fraction of water use by Reservoir on the subcatchment level	dimensionless	see table in GenRiver Model sector SubcResDynamics	Input Section/Lake
6.	G_GrassLitConv	Weighting value of grass to contribute the litter	dimensionless	(1)	Input Section/Cattle & Grass
7.	G_GrassMortFrac	Mortality factor of the grass	dimensionless	(0.03)	Input Section/Cattle & Grass
8.	G_GrazingManConv	Weighting value of artificial grazing factor	dimensionless	(0.1)	Input Section/Cattle & Grass
9.	G_SurfLitDecFrac	Fraction of decaying litter on the soil surface	dimensionless	(0.03)	Input Section/Cattle & Grass
10.	G_SurfManureDecFrac	Fraction of decaying manure on the soil surface	dimensionless	(0.01)	Input Section/Cattle & Grass

11.	G_TramplingMultiplier	Multiplication of Trampling factor	dimensionless	0 – 2 (0)	Input Section/Cattle & Grass
12.	G_WUE	Water use efficiency of grass	dimensionless	(0.04)	Input Section/Cattle & Grass
13.	I_Area[Subcatchment]	Area of each subcatchment	km^2	-	(SubCatchInfo)
14.	I_AvailWaterConst	Constant value of water availability for plant	mm	0 – 1000 (300)	Input Section/Soil and Plant Water
15.	I_CaDOYStart	Day of year at which simulation starts	Julian days	0 – 365 (0)	Run & Output Section/Initial Run
16.	I_DailyETYear…to…	Daily potential evapotranspiration	mm	(see table in Excel sheet LandCoverData)	(LandCoverData)
17.	I_DailyRainYear…to…	Daily rainfall for each unit Sub catchment	mm	(see table in Excel sheet RainData)	(RainData)
18.	I_DamInThisStream? [Subcatchment]	The option to decide is whether the subcathment has Dam or not. 0 = no dam, 1 = yes	dimensionless	0 or 1 (0)	Input Section/River
19.	I_Evapotrans	Potential evapotranspiration (Penmann type)	mm	(see table in Excel sheet LandCoverData)	(LandCoverData)
20.	I_EvapotransMethod	The option to choose is whether the simulation using daily or monthly data of evapotranspiration. 0 = use daily data, 1 = use monthly data	dimensionless	1 – 2 (1)	Input Section/Soil and Plant Water
21.	I_FracVegClass1…4[VegClass]	Land cover class frequency for each subcatchment for four of years of landcover change transition	dimensionless	(see table in Excel sheet LandCoverData)	(LandCoverData)
22.	I_GWRelFrac1…4	Daily groundwater release fraction for each subcatchment for four of years of landcover change transition	dimensionless	(see table in Excel sheet SubCatchInfo)	(SubCatchInfo)
23.	I_GWRelFracConst	Constant value of daily groundwater release fraction	mm	0 – 1 (0.03)	Input Section/Soil and Plant Water

24.	I_GWRelFracConst?	Switch to decide an option to have a constant groundwater release fraction and constant maximum groundwater store. Value 0 means constant for groundwater release fraction and irregular for maximum groundwater storage capacity, value 1 means irregular for groundwater release fraction and constant for maximum groundwater storage capacity.	dimensionless	0 – 1 (0)	Input Section/Soil and Plant Water
25.	I_InitRelGW	Initial groundwater store relative to maximum value	dimensionless	0 – 1 (1)	Input Section/Soil and Plant Water
26.	I_InitRelSoil	Initial soil water content relative to field capacity	dimensionless	0 – 2 (1)	Input Section/Soil and Plant Water
27.	I_InputDataYears	Year of transition of land cover change	year	(see table in Excel sheet LandCoverData)	(LandCoverData)
28.	I_InterceptClass[LandCoverType]	Interception storage capacity per land cover class	mm	(see table in Excel sheet LandCoverData)	(LandCoverData)
29.	I_InterceptEffectonTransp	Weighted factor of Transpiration affected by water Interception	dimensionless	0 – 1 (0.5)	Input Section/Soil and Plant Water
30.	I_MaxDynGWConst	Constant value of dynamic groundwater storage capacity	mm	1- 2000 (350/100)	Input Section/Soil and Plant Water
31.	I_MaxDynGWSub1…4 [Subcatchment]	Dynamic groundwater storage capacity for each subcatchment for four of years of landcover change transition	mm	(see table in Excel sheet SubCatchInfo)	(SubCatchInfo)
32.	I_MaxInf	Maximum infiltration capacity	mm day^{-1}	30 – 1000 (720)	Input Section/Soil and Plant Water
33.	I_MaxInfSSoil	Maximum infiltration capacity of sub soil	mm day^{-1}	0 - 1000 (120)	Input Section/Soil and Plant Water

34.	I_MultiplierEvapoTrans [LandCoverType]	Multiplier of potential evapotranspiration for each vegetation class and subcatchment	dimensionless	(see table in Excel sheet LandCoverData)	(LandCoverData)
35.	I_PercFracMultiplier	Multiplier of fraction of water percolation	dimensionless	0 – 10 (0.13)	Input Section/Soil and Plant Water
36.	I_PlantAvWatSub1…4	Value of water availability for plant for each subcatchment for four of years of landcover change transition	mm	(see table in Excel sheet Soil Properties)	(Soil Properties)
37.	I_PowerInfiltRed	Degree of Power equation	dimensionless	3-3.5 (3.5)	Input Section/Soil and Plant Water
38.	I_PWPSub1…4	Permanent wilting point Parameter	mm	(see table in Excel sheet Soil Properties)	(Soil Properties)
39.	I_RainCycle?	Parameter governing ways to read rainfall data. 0 = use multiple year rainfall data, 1 = use 1 year data in cycle/continuously)	dimensionless	0 or 1	Input Section/Rainfall
40.	I_RainGenSeed	Seed random generator for rainfall rate	dimensionless	(300)	Input Section/Rainfall
41.	I_RainIntensCoefVar	Coefficient of variation of rainfall intensity	dimensionless	0 – 1 (0.3)	Input Section/Rainfall
42.	I_RainIntensMean	Average rain intensity per hour. Rain intensity is a factor affecting water infiltration. It is assumes to follow normal distribution with an average of Rain_IntensMean and standard deviation Rain_IntensMean*Rain_IntensCoefVar	mm day^{-1}	1 – 100 (30)	Input Section/Rainfall
43.	I_RainIntercDripRt	The rate of water dripping from water on interception surface	mm hr^{-1}	5 – 15 (10)	Input Section/Soil and Plant Water
44.	I_RainMaxIntDripDur	Maximum value of water interception delay before start to dripping	mm hr^{-1}	0 - 5 (0.5)	Input Section/Soil and Plant Water

45.	I_RainMultiplier	Multiplier of rainfall for quick modifications of rainfall amount	dimensionless	1 - 5 (1)	Input Section/Rainfall
46.	I_RainYearStart	Initial year based on rainfall data at which simulation starts	dimensionless	0 – 25 (0)	Run & Output Section/Initial Run
47.	I_RelDroughtFact[LandCoverType]	Drought limitation to transpiration per land cover class relative to field capacity	dimensionless	(see table in Excel sheet LandCoverData)	(LandCoverData)
48.	I_RFlowDataYear…to…	Daily discharge data for each unit Subcatchment	mm	(see table in Excel sheet DebitData)	(DebitData)
49.	I_River flowDispersalFactor	The dispersal pattern flow patch of river	dimensionless	0.01 – 1 (0.3)	Input Section/River
50.	I_RivFlowTime1…4	Ratio of time arrival of river flow per subcatchment	dimensionless		(SubCatchInfo)
51.	I_RoutingDistance	Distance from centre of subcatchm ent to measurement point	km	(see table in Excel sheet SubCatchInfo)	(SubCatchInfo)
52.	I_RoutVeloc_m_Per_s	River flow velocity	m sec^{-1}	0.001 – 25 (0.4)	Input Section/River
53.	I_SoilPropConst?	Switch to decide an option to have a constant value of water ava ilability for plant and soil saturation. Value 0 means irregular, value 1 means constant.	dimensionless	0 or 1 (0)	Input Section/Soil and Plant Water
54.	I_SoilQFlowFrac	Fraction of soil quick flow	dimensionless	0 – 2 (1)	Input Section/Soil and Plant Water
55.	I_SoilSatminFCConst	Constant value of difference between saturation water storage capacity and field capacity of the soil	mm	0 – 500 (100)	Input Section/Soil and Plant Water
56.	I_SoilSatMinFCSub1…4 [Subcatchment]	Difference between saturation water storage capacity and field capacity of the soil for each vegetation class and subcatchment for four years of simulation transition	mm	(see table in Excel sheet Soil Properties)	(Soil Properties)
57.	I_SpatRain1…7[Subcatchment]	Daily rainfall for each unit Subcatchment generated from SpatRain module.	mm	see graph in initialization	Model Sector (I_Rainfall)

58.	I_SurfLossFrac	Fraction of surface flow loses	dimensionless	0 – 1 (0)	Input Section/River
59.	I_TopSoilBD_BDRef1…4	Value of Top soil BD/BDref	dimensionless	(see table in Excel sheet Soil Properties)	(Soil Properties)
60.	I_Tortuosity	Measured distance/real path length of streams	dimensionless	0 – 1 (0.4)	Input Section/River
61.	I_UseSpatVarRain?	Switch to decide an option to use spatial rainfall distribution generated from SpatRain module. Value 1 means using spatial rainfall distribution generated from SpatRain module.	dimensionless	0 or 1	Input Section/Rainfall
62.	I_WarmUpTime	Time to initialize the values of water stocks	day	0 – 730 (365)	Run & Output Section/Initial Run
63.	L_FloodTresh	Beginning of the flooding event	m	(363)	InputSection/Lake
64.	L_HEPPActive?	Option to switch on the HEPP operating procesures		0 or 1	InputSection/Lake
65.	L_Lake?[Subcatchment]	Switch to decide an option whether the subcatchment lake or not. Value 1 means lake	dimensionless	0 or 1	Input Section/Lake
66.	L_LakeBottomElev	Bottom Lake Elevation	m (ASL)	(160)	Input Section/Lake
67.	L_LakeElevPreHEPP	Lake Elevation of pre Operating HEPP	m (ASL)	(362.3)	Input Section/Lake
68.	L_LakeLevelFullHEPP	Lake level of Full Operating HEPP	m	(362.3)	InputSection/Lake
69.	L_LakeLevelHalfHEPP	Lake level of Full Operating HEPP	m	(361.8)	InputSection/Lake
70.	L_LakeLevelNoHEPP	Lake level of Full Operating HEPP	m	(359.5)	InputSection/Lake
71.	L_LakeOverFlowFrac	Fraction of Overflow	dimensionless	(0.1)	InputSection/Lake
72.	L_LakeOverFlPostHEPP	Overflow post operating HEPP	m	(362.6)	InputSection/Lake

73.	L_LakeOverFlPow	Overflow power	m	(4)	InputSection/Lake
74.	L_LakeTranspMultiplier	Multiplication of Lake Evapotranspiration rate	dimensionless	0 – 5 (1)	InputSection/Lake
75.	L_m3_per_kwh	Water requirement to produce Electricity per kwh	m^3	(1584)	
76.	L_QmecsHEPP	Inflow to HEPP	m^3	(47.1)	InputSection/Lake
77.	L_QmecsSanFlow	Sanitary Flow		(3)	
78.	L_ResrDepth	The depth of reservoir	m	(10000)	InputSectioo/Lake
79.	O_MperiodeLength[MeasurePeriode]	Daily simulation period	day	(365)	Run & Output Section/Initial Run
80.	O_StartDOY[MeasurePeriode]	Starting day to begin simulation	day	(0)	Run & Output Section/Initial Run
81.	O_StartMYear[MeasurePeriode]	Starting year of begin simulation	year	(1,2,3)	Run & Output Section/Initial Run
82.	S_TrampMax	Maximum soil tramping factor	dimensionless	(100)	Input

Appendix 2. List of Output Parameters

Abbreviation used in parameter names

No	Acronym	Definition
1.	D	Dynamic
2.	I	Input/Initialization
3.	O	Output
4.	L	Lake

No	Acronym	Definition	Unit	Location
1.	D_InitLakeVol	Initial lake water volume	mm	Complete Simulation
2.	D_Tot River flowNoDelay	Cumulative amount of river flow without delay	mm	Complete Simulation
3.	I_DailyRain	Daily rainfall	mm	- Table Model Performance & Watershed Indicator – Page 1
4.	I_RFlowData mmday	Daily amount of actual river flow data for the whole subcatchment	mm	a. Table Model Performance & Watershed Indicator – Page 1 b. Graph Water Balance – Page 1 & 6 c. Table Water Balance – Page 1
5.	L_CumHEPPUse	Cumulative Water use to operate HEPP	kwh	Table HEPP
6.	L_HEPP kwh	Hydro power per m^3 water flow	10^6 kwh	Graph HEPP
7.	L_HEPPOpTimeRel	Optimalization of time Operating HEPP	dimensionless	Complete Simulation
8.	L_HEPPWatUseFlow	The flow of Water use by HEPP	mm	Graph HEPP
9.	L_InflowtoLake	Daily amount of river water flows to Lake	mm	Table Model Performance & Watershed Indicator – Page 1 Graph Water Balance – Page 1 & 6 Table Water Balance – Page 1

10.	L_LakeLevel	Level of water in the lake	m	Graph HEPP
11.	L_LakeVol	Volume water in the lake	m^3	Graph HEPP
12.	L_RivOutFlow	Lake Outflow to the river	mm	- Table Model Performance & Watershed Indicator – Page 1
13.	O_BaseFlowAcc	Daily amount of base flow for the whole subcatchment and vegetation class	mm	- Table Model Performance & Watershed Indicator – Page 1 - Graph Water Balance – Page 3 - Table Water Balance – Page 1
14.	O_BestYHEPP	The Best year Estimation of HEPP operating	kwh	Table HEPP
15.	O_ChkAllCatchmAccFor?	Overall balance of input and output of water in catchment level	mm	Complete Simulation
16.	O_ChkAllLakeAccFor?	Overall balance of input and output of water in lake level	mm	Complete Simulation
17.	O_ChkAllRiverAccFor?	Overall balance of input and output of water in river level	mm	Complete Simulation
18.	O_CumBaseFlow	Cumulative amount of base flow the whole subcatchment and vegetation class	mm	- Table Water Balance – Page 2 - Graph Water Balance – Page 5 - Complete Simulation
19.	O_CumBaseFlowMP[MeasurementPeriod]	Cumulative amount of base flow for the whole subcatchment and vegetation class for each transition period	mm	Subcatchment Balance
20.	O_CumDebitDataMP[MeasurementPeriod]	Cumulative amount of actual river flow data for the whole subcatchment for each transition period	mm	Subcatchment Balance
21.	O_CumDebitPredMP[MeasurementPeriod]	Cumulative amount of prediction river flow data for the whole subcatchment for each transition period	mm	Subcatchment Balance
22.	O_CumDeepInfilt	Cumulative amount of water deeply infiltrate to the soil for the whole subcatchment	mm	- Table Water Balance – Page 2 - Graph Water Balance – Page 5
23.	O_CumETLandMP[MeasurementPeriod]	Cumulative amount of evapotranspiration for the whole subcatchment and vegetation class for each transition period	mm	Subcatchment Balance

24.	O_CumEvapotrans	Cumulative amount of evapotranspiration	mm	- Table Water Balance – Page 2 - Graph Water Balance – Page 4
25.	O_CumEvapotransMP[MeasurementPeriod]	Cumulative amount of evapotranspiration for each transition period	mm	Subcatchment Balance
26.	O_CumHEPPOutflowMP[MeasurementPeriod]	Cumulative HEPP Outflow on Each Transition Period	mm	Lake/HEPP
27.	O_CumInfiltration	Cumulative amount of water infiltrate to the soil for the whole subcatchment	mm	- Table Water Balance – Page 2 - Graph Water Balance – Page 4
28.	O_CumInfiltrationMP[MesurementPeriod]	Cumulative amount of infiltration for each transition period	mm	Subcatchment Balance
29.	O_CumInterceptEvap	Cumulative amount of water evaporated from intercepted water for the whole subcatchment and vegetation class	mm	- Table Water Balance – Page 2 - Graph Water Balance – Page 4 - Complete Simulation
30.	O_CumInterceptEvapMP[MeasurementPeriod]	Cumulative amount of evaporated interception water for each transition period	mm	Subcatchment Balance
31.	O_CumPercolation	Cumulative amount of percolation water for the whole subcatchment	mm	- Table Water Balance – Page 2 - Graph Water Balance – Page 5
32.	O_CumRain	Cumulative amount of daily rainfall for the whole subcatchment and vegetation class	mm	- Table Water Balance – Page 2 - Graph Water Balance – Page 4 & 5 - Complete Simulation
33.	O_CumRainMP[MeasurementPeriod]	Cumulative amount of daily rainfall for the whole subcatchment and vegetation class for each transition period	mm	Subcatchment Balance
34.	O_CumRivInflowToLakeMP[MeasurementPeriod]	Cumulative amount of river water flows to Lake on each transition period	mm	Lake/HEPP
35.	O_CumRivOutFlowMP[MeasurementPeriod]	Cumulative amount of river water out flow for each transition period	mm	Lake/HEPP
36.	O_CumSoilQFlow	Cumulative amount of soil quick flow for the whole subcatchment and vegetation class	mm	- Table Water Balance – Page 2 - Graph Water Balance – Page 5 - Complete Simulation
37.	O_CumSoilQFlowMP[MeasurementPeriod]	Cumulative amount of soil quick flow for the whole subcatchment and vegetation class for each transition period	mm	Subcatchment Balance

38.	O_CumSurfQFlow	Cumulative amount of surface quick flow for the whole subcatchment and vegetation class	mm	- Table Water Balance – Page 2 - Graph Water Balance – Page 4 - Complete Simulation
39.	O_CumSurfQFlowMP[MeasurementPeriod]	Cumulative amount of surface quick flow for the whole subcatchment and vegetation class for each transition period	mm	Subcatchment Balance
40.	O_CumTransp	Cumulative amount of evapotranspiration for the whole subcatchment and vegetation class	mm	Complete Simulation
41.	O_CumTranspMP[MeasurementPeriod]	Cumulative amount of transpiration for each transition period	mm	Subcatchment Balance
42.	O_DeepInfAcc	Current deep infiltration	mm	- Table Water Balance – Page 1 - Graph Water Balance – Page 3
43.	O_DeltaGWStock	Changing in ground water stock	mm	Complete Simulation
44.	O_EvapotransAcc	Current evapotranspiration	mm	- Table Model Performance & Watershed Indicator – Page 1 - Graph Water Balance – Page 1
45.	O_FrBaseFlow	Cumulative amount of base flow relative to cumulative amount of river flow	mm	- Lake/HEPP - Table HEPP
46.	O_FrSoilQuickflow	Cumulative amount of soil quick flow relative to cumulative amount of river flow	mm	- Lake/HEPP - Table HEPP
47.	O_FrSurfQuickFlow	Cumulative amount of surface quick flow relative to cumulative amount of river flow	mm	- Lake/HEPP - Table HEPP
48.	O_HEPP kwh per day[MeasurementPeriod]	Amount of water used in mm day^{-1} for whole catchment	mm	Lake/HEPP
49.	O_InfAcc	Current infiltration	mm	- Table Water Balance – Page 1 - Graph Water Balance – Page 2
50.	O_IntercAcc	Daily amount of water evaporated from intercepted water for the whole subcatchment and vegetation class	mm	- Table Model Performance & Watershed Indicator – Page 1 - Table Water Balance – Page 1 - Graph Water Balance – Page 2

51.	O_PercAcc	Current percolation	mm	- Table Water Balance – Page 1 - Graph Water Balance – Page 3
52.	O_RainAcc	Daily amount of rainfall for the whole subcatchment	mm	a. Table Model Performance & Watershed Indicator – Page 1 b. Graph Water Balance – Page 2 & 3 c. Table Water Balance - 1
53.	O_RelOpTimeHEPP[Measurement Period]	Time operating of HEPP per simulation period	mm	Lake/HEPP
54.	O_SoilQFlowAcc	Daily amount of soil quick flow for the whole subcatchment and vegetat ion class	mm	- Table Model Performance & Watershed Indicator – Page 1 - Table Water Balance – Page 1 - Graph Water Balance – Page 3
55.	O_SurfQFlowAcc	Daily amount of surface quick flow for the whole subcatchment and vegetation class	mm	- Table Model Performance & W atershed Indicator – Page 1 - Table Water Balance – Page 1 - Graph Water Balance – Page 2
56.	O_TotStream flow	Cumulative amount of surface quick flow, soil quick flow and base flow for the whole subcatchment and vegetation class	mm	Complete Simulation
57.	O_WorstYHEPP	The Worse year Estimation of HEPP operating	kwh	Table HEPP

Appendix 3. Advice on dealing with input parameters data

A. How to get rainfall depth over the watershed?

It is difficult to obtain an average depth of rainfall from data of several rain gauges because the results are influenced by the number and locations of gauges and the storm variability. There are several methods that can be used of estimating rainfall depth over the watershed.

1) Use of one gauge

How well does the rainfall measured at a single gauge represent the average depth of rainfall over the watershed? It depends on:

- distance from the gauge to the centre of the area,
- size of the area,
- kind of rainfall amounts being used, and
- orographics (topography) of the locality.

Storm rainfall caught at the gauge was seen to be quite close to those of the watershed averages, which were determined using a dense network of gauges.

2) Isohyetal method

Isohyetal maps are often used, with networks of any configuration, to get area averages or for studies of rainfall distributions. An isohyet is a line connecting points of equal rainfall depth. The map is made by drawing the lines in the same manner that contour lines are drawn on topographic maps, using the gauge locations as data points.

3) Thiessen method

In this method, a watershed area is divided into sub-areas using rain gauges as hubs of polygons. The sub-areas are used to determine ratios that are multiplied by the sub-area rainfall and summed to get the watershed average depth.

4) Other methods

Other methods for estimating areal average rainfall from a system of point rain gauge measurements include the reciprocal-distance-squared method and use of geostatistics (krieging).

(Adapted from Chapter 4: Storm Rainfall Depth. 1993. Hydraulics and Hydrology: Technical References. NRCS National Engineering Handbook. USDA).

B. Are You Sure of Your Rainfall Data Quality?

Assessing the errors of rainfall data is important, since they become a prime driver in hydrological models. Rainfall data commonly is obtained from manual stations which usually have errors such as instrument malfunctioning, misreading of water amount or date or the operator not making the daily walk to the gauge. To make sure how good is your rainfall time series data you could conduct this test.

1. Correlation analysis test of the consistency of data

The nearby stations have a higher correlation than ones further away. Data was perceived reliable if they have consistence correlation with the other locations over time.

2. Homogeneity test

1. Absolute homogeneity testing

   The data were checked for homogeneity using a likelihood ratio test performed on a ratio or difference series between the candidate station and a reference series.

2. Relative homogeneity testing

   Candidate rainfall series is compared with a reference series. The choice of a reference series leaves room for subjective decisions. Other relative homogeneity tests are the Alexandersson test or standard normal homogeneity test (SNHT), a bivariate test of Maronna , and the Easterling and Peterson test. The rainfall data of months that had a larger than 95% probability of being an outlier .

3. Meta-data control

Comparing notes with observers who keep their own archive allows completion and cross-checking (Verbist 2007 Pers comm).

C. Obtaining Stream Flow Data for Ungauged Sites

Project sites are usually located on small or moderate-sized streams that do not have operating stream gauges. Locating stream flow data applicable to these sites for the purpose of making hydrologic analyses can be difficult. Generally there are two options for finding appropriate data:

1. Use stream flow values from a nearby gauged site that has the same drainage area size.
2. Scale down the stream flow values from a gauge on a larger nearby watershed to the size of the drainage area of the project stream.

1. Using stream flow values from a gauged site of the same size

Step 1: Determine the drainage area of the project site.

Step 2: Locate a gauged site with a drainage area similar in size to that of the project site.

Step 3: From the list of gauged sites with a similar drainage area identify the ones that may be located in similar topographic and climatic zones as the project site. For example, if the project site is located in a coastal basin it would not be appropriate to use stream flow values from a gauged site that had a much drier or wetter regime and vastly different topography.

When using a different stream to estimate stream flow values for a project site, it is important to consider several factors.

1. Drainage areas are similar.
2. Topography is similar (mountainous, desert, valley etc).
3. Climatic patterns should be similar (precipitation patterns, snow accumulation etc).
4. Soil characteristics should be similar (porous, impermeable etc).
5. Land use should be similar (forested, urban, agricultural etc).
6. Length of period of record.

The more components that are similar between the two basins, the more likely it is that the stream flow values from the gauged site will accurately depict the stream flow characteristics of the project site.

2. Scaling down stream flow values for a large watershed

The project site may be located on a small part of a larger basin or the only gauged stream with similar topographic characteristics may have a large drainage area. For example, the project site may be on a small creek that is a tributary to a large river. The large river may be gauged near its mouth where the drainage area is quite large.

Step 1: Determine the drainage area of the project site.
Step 2: Determine if the project stream is part of a larger gauged basin.
Step 3: Determine the drainage area of the large basin.
Step 4: Calculate the proportionality (Drainage Area Ratio) between the project site drainage area and the drainage area of the gauged watershed.
Step 5: Scale down stream flow values by this ratio.

The size of a watershed affects the hydrologic characteristics of that drainage area. A small watershed responds to storms very differently from a large basin. Most of the precipitation on a small watershed tends to run off quickly because there is little time or area for infiltration. On a large basin, travel distances are much longer, channel storage may diminish flow peaks, precipitation has more time to infiltrate and runoff reaches the basin outlet more slowly after peak rainfall than in a small watershed, such that the discharge per unit area is usually smaller. It is advisable to keep in mind that stream flow values from a large basin may not accurately represent the hydrologic characteristics of a smaller watershed for the reasons given.

(From Stream flow Evaluations for Watershed Restoration Planning and Design: an interactive guide and tutorial with examples of Oregon streams. Tips for manipulating and managing data. Oregon State University. 2002–2005. Available from http://water.oregonstate.edu/stream flow/)

D. If evapotranspiration data are not available

Evapotranspiration can be estimated using the Penman Monteith or Thornwaite equation or you can use a reference evapotranspiration rate.

Reference evapotranspiration rate (Coster 1937. In: Asdak 1995)

Vegetation Type	Evapotranspirat ion Rate (mm/year)
Kirinyu (*Chromolaena odorata*)	
Good soil	2900
Medium	1600–2000
Bad soil	1000
Imperata cylindrical	
High rainfall (e.g Bogor)	1750
Low rainfall (e.g East Java)	1000
Acacia villosa	
High rainfall (e.g Bogor)	2400
Low rainfall (e.g East Java)	1600
Sengon (*Albizia falcataria*)	
High rainfall (e.g Bogor)	2300
Tea	900
Rubber (Bogor)	1300
Bamboo (good soil)	3000
Teak	
Good soil	1300–1400
Medium	800–1000
Bad soil	1100–1200
Mountainous Forest	
1000 m asl	1200
2500 m asl	500–600
Average	564

E. How to extract hydrologic information from spatial data

To generate hydrological features (subcatchment boundary, river network and routing distance) of GenRiver, you can use the HEC-Geohms tool that has been embedded in Arc view and Arc Gis (ESRI) (www.hec.usace.army.mil). This has been developed as a geospatial hydrology tool for engineers and hydrologists with limited GIS experience. The process of generating input data for the basin component of HMS has been divided into seven analysis steps: (1) raster-based terrain analysis; (2) raster-based watershed and stream network delineation; (3) vectorization of watersheds and stream segments; (4) topologic analysis; (5) computation of hydrologic parameters of the watersheds; (6) computation of hydrologic parameters of the stream segments; and (7) writing of an HMS basin model (Olivera PE. 2001. Extracting hydrologic information from spatial data for HMS modelling. Journal of Hydrologic Engineering 6(6)).

The Arc Hydro Toolset can be download freely from the website. The toolkit facilitates the creation, manipulation and display of Arc Hydro features and objects within the ArcMap environment. The tools provide raster, vector and time series functionality and many of them populate the attributes of Arc Hydro features.
(http://www.crwr.utexas.edu/giswr/hydro/ArcHOSS/Downloads/index.cfm).

F. Reference of canopy interception

Vegetation parameter values derived from Land Cover Data from NASA LDAS Vegetation Database with IGBP classification 1 km AVHRR imagery C. Bandaragoda et al. 2004. Journal of hydrology 298: 178-201

Class	Canopy Capacity mm	Canopy evapotranspiration enhancement	Albedo
Unclassified	0	1	0.23
Evergreen needleleaf forest	3	3	0.14
Evergreen broadleaf forest	3	3	0.14
Deciduous needleleaf forest	3	3	0.14
Deciduous broadleaf forest	3	3	0.14
mixed forest	3	3	0.14
closed shrublands	2	2	0.2
open shrublands	1.5	1.5	0.2
Woody Savannah	1.5	1.5	0.2
Savannah	1.5	1.5	0.2
Grassland	1	1	0.26
Permanent Wetland	1	1	0.1
Croplands	1	1	0.26
Urban/developed	1	1	0.3
Natural Vegetation	1.5	1.5	0.2

Vegetation Type	Soil Moisture
Grass land	75
Potatoes	100
Rice field, wheat etc	140
Forest	400

To search the values of relative drought threshold, you can use the root constant values and the soil moisture content (Shaw 1985) as a reference

Appendix 4. Advice on calibration process of GenRiver model

The result of the simulation should be close to the observation value. It can be explored through several procedures.

1. Input your watershed parameters and run the model.
2. Observe your hydrograph on hydrological year by:
   a. Plot simulation result against the observation
   The hydrograph will move to downstream as a wave of quickly increasing discharge due to the overland flow then decreasing discharge to the base flow. The factors influencing hydrograph shape are river velocity, drainage density and basin shape. The inputs related to the hydrograph in GenRiver are:
   i. River flow velocity
   ii. Tortuosity
   iii. Dispersal factors

The speed of increasing discharge is related to the overland flow parameter and the speed of decreasing discharge is related to interflow or groundwater release parameter.

Check your simulation and return to your parameter setting.

b. Plot annual cumulative river flow per unit rainfall

The graph shows the pattern of accumulation flow over the period. Similar to the hydrograph, the cumulative graph shows the stages of the saturation process: if the watershed rapidly saturates or runoff dominates, the graph appears like a positive logarithmic curve. However, if the watershed has high storage capacity in the first stage, the water will fill the soil and the graph will show a positive exponential curve.

Look at your simulation graph and then check your parameters related to infiltration and ground water parameters.

Approximate average velocities in m s^{-1} of runoff (Chow 1988)

	Slope					
	0-3%		4-7%		8-11%	
Channels	**min**	**max**	**min**	**max**	**min**	**max**
Woodland	0.00	0.46	0.46	0.76	0.76	0.99
Pastures	0.00	0.76	0.76	1.07	1.07	1.30
Cultivated	0.00	0.91	0.91	1.37	1.37	1.68
Pavement	0.00	2.59	2.59	4.11	4.11	5.18
Well-defined channel			Manning			
Natural/not well defined	0.00	0.61	0.61	1.22	1.22	2.13

The calibration process is time consuming. You should judge your model performance as “satisfactory” if NSE > 0.50.

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